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WHAT CAN POLICYMAKERS LEARN FROM GERMANY'S INDUSTRIE 4.0 DEVELOPMENT STRATEGY?

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What can policymakers learn from Germany's *Industrie 4.0* development strategy?

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I4.0	Industry 4.0
Acatech	Deutsche Akademie der Technikwissenschaften (German Academy of the Technical Sciences)
BITKOM	Bundesverband Informationswirtschaft, Telekommunikation und neue Medien (Federal Association for Information Economy, Telecommunications and New Media)
BMBF	Bundesministerium für Bildung und Forschung (Ferderal Ministry for Education and Research)
BMI	Bundesministerium des Inneren (Federal Ministry of the Interior)
BMUB	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety)
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry of Transport and Digital Infrastructure)
BMWi	Bundesministerium für Wirschaft und Energie (Federal Ministry of Economic Affairs and Energy)
CIM	Computer-Integrated-Manufacturing
CPS	Cyber-Physical Systems
CPPS	Cyber-Physical-Production-Systems
DA	Digitale Agenda (Digital Agenda)
DDI	Data-Driven Innovation
DFKI	Deutsches Forschungszentrum für Künstliche Intelligenz (German Research Center for Artificial Intelligence)
EFI	Expertenkommission Forschung und Innovation (Expert Commission Research and Innovation)
HTS	Hightech-Strategie
ICT	Information and Communication Technology
IIoT	Industrial Internet of Things
IoT	Internet of Things
LNI4.0	Labs Network Industry 4.0
MIC	Middle-Income Country

MNC	Multinational Corporation
NPR	Next Production Revolution
PI4.0	Plattform Industrie 4.0
R&D	Research and Development
RAMI4.0	Reference Architecture Model Industry 4.0
SCI4.0	Standardization Council Industry 4.0
SME	Small- and Medium Enterprise
VDMA	Verband Deutscher Maschinen- und Anlagenbauer (Mechanical Engineering Industry Association)
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie (Association of the Electro-Technical and Electronic Industries)

Abstract

Industrie 4.0 lies at the core of Germany's efforts to sustain its global leadership in innovation and manufacturing. While many countries seek to emulate Germany's approach to I4.0, few possess a comparable foundation of accumulated technological and manufacturing capabilities. Followers, peers and potential competitors need to objectively appraise the efforts Germany has made and its sheer commitment of resources over the last few years to become both a leading supplier and the most important market for I4.0-related technologies, products and services. This paper discusses the policy processes, actors involved—as well as their roles and interactions over time—and the type of instruments Germany has implemented in its quest for I4.0. The evidence, albeit sparse, suggests that Germany's I4.0 strategy can best be described as policy experimentation and as a learning process integrating a complex mix of innovation, industrial, research and other related policies. The German experience underscores the relevance yet again of multi-stakeholder coordination and collaboration as the foundation for the design and implementation of coevolving innovation and industrial policies.

Keywords: Industry 4.0; Germany; innovation policy mix; industrialization

JEL codes: L52, O14, O52.

1. Introduction

The term "Industry 4.0" (hereafter I4.0) is pervasive in research, policy and business circles (Liao et al., 2017); it is used to summarize technological and organizational trends related to the development of global manufacturing. It was, however, initially coined in Germany as *Industrie 4.0* (I4.0) to represent the country's strategic vision of the future and represents an ambitious bid to preserve global manufacturing leadership by reaffirming commitment to economic and social transformation through innovation, collective and multi-stakeholder participatory processes and policy experimentation (Pfeiffer, 2017). The rapid diffusion of the term I4.0 across the globe has positioned Germany as a reference for strategic approaches to harnessing the Fourth Industrial Revolution.[1] Germany was quick to capitalize on this by introducing I4.0 as part of the G20 agenda when it assumed the presidency in 2016.

German organizations actively collaborate with partners in both developed and developing countries to enable mutual readiness and a smooth transition towards I4.0. Partnerships involve German organizations and partners in Japan, France, Italy, Australia and Czechia (BMWi, 2018b). (OECD, 2017) documents the strong influence of Germany's I4.0 on the *Made in China 2025* strategy and the expected contribution cooperation with German institutions is expected to have on the delivery of China's ambitious goals. (Santiago, 2018) has also identified strategic collaborations between organizations in Brazil, Egypt, India, Kazakhstan, Mexico, Malaysia, Thailand and Viet Nam with German partners. Collaboration covers several areas, from investment in and mobilization of science, technology and innovation capacities, through the facilitation of industrial promotion initiatives or joint awareness raising activities targeting domestic agents, to the setting up of technology transfer offices to assist host countries in becoming regional hubs for I4.0 technologies and services.

This paper supports propositions made in recent contributions to the literature: first, to avoid a "hype" in the face of the genuinely revolutionary nature of the transformations that can be associated with I4.0 (OECD, 2017; Reischauer, 2018), and second, to critically appraise the merits of existing approaches to it (Pfeiffer, 2017; Santiago, 2018). (OECD, 2017) asserts that the next production revolution should also be understood from the perspective of trust in government, particularly in scientific and regulatory authorities, who face public resistance to new, disruptive technologies and diminished trust in government action. Policymakers should be wary of those offering coherent, proven, "one-size-fits-all" strategies around I4.0 (Liao et al.,

[1] The term "Industry 4.0", or derivations thereof, is often found in the titles of other national I4.0 strategies in both developed and developing countries (Reischauer, 2018). Italy and Thailand are two examples (Board of Investment, 2017; Ministry of Economic Development, 2016). In stark parallel to Germany's vision, *Thailand 4.0* captures the country's aspiration to attain a new development stage where manufacturing plays a prominent role.

2017). The merits of Germany's approach to I4.0 need to be critically assessed so that objective inputs inform strategic policy responses and balanced with evidence on the merits of alternative models.[2] This paper contributes to debates around the following overarching questions: What lessons can be gleaned from Germany's approach to I4.0? Are there suitable examples of interventions to promote I4.0 in developing countries? What are the do's and don'ts regarding the design and implementation of I4.0-related strategies?

This paper proceeds as follows: Section 2 describes the methodology underpinning this study. Section 3 provides an overview of what I4.0 is all about. Section 4 chronologically traces the development of Germany's I4.0 strategy. The traditional "dual approach" used to describe this strategy fails to capture the full complexity of the country's efforts to become a leading market and supplier of I4.0. Section 5 contends that Germany's I4.0 exemplifies a complex policy learning and policy experimentation exercise; it simultaneously stems from and contributes to a broader, highly ambitious industrial- and innovation-driven development strategy. In the process of developing an I4.0 strategy, German authorities have been able to identify and built on existing interventions, particularly from private sector organizations. While a detailed analysis of those distinct interventions and projects is outside the scope of this paper, Section 6 introduces one of the most emblematic instruments of the strategy, namely *Plattform Industrie* I4.0 (PI4.0). Section 7 concludes with a discussion on the relevance and implications of Germany's I4.0 strategy for other countries.

2. Methodology

We conducted a systematic review of German government policy documents and related evidence from academic and grey literature. About 179 documents in either English or German were retrieved from different government and non-government organizations. These documents were examined for their relevance to derive a chronological account of I4.0-related policy interventions. The time period covered stretched roughly from 2006 to 2017.[3] The analysis of this material builds on (López-Gómez et al., 2017) who argue that policy interventions to foster I4.0 can be clustered into three main categories: (1) developing framework conditions through investments in infrastructure and suitable institutional and economic environments; (2) fostering specific I4.0 enabling factors through dedicated programmes, facilities and incentives mechanisms; and (3) enhancing vocational training and higher education programmes around

[2] (Khurana et al., 2018) for example, quote a 2016 study conducted by Bitkom Research in which the perceived leadership in driving the development of I4.0 was slightly in favour of the United States. Of a total of 559 industrial enterprises in the study, 28 per cent declared the United States was the leader, while 25 per cent claimed Germany was.

[3] This timeframe is slightly larger than the 2009-2015 period considered by (Pfeiffer, 2017).

I4.0-related competencies in ways that anticipate the implications of I4.0 on skills, employability and the functioning of education systems.

The data collection focused on identifying policy instruments underpinning Germany's I4.0 strategy. To the best of our knowledge, only very few available reviews of the German I4.0 strategy depict it by looking at policy instruments, projects and other interventions carried out by government, private sector or academic organizations. The intention was twofold: first, to make sense of the complexity of different innovation policy instruments; and second, to shed light on the choices made and the policy goals that guided innovation policy formulation (Borrás and Edquist, 2013). As will become apparent from the discussion in Section 4 and Section 5, the development path followed by Germany's I4.0 strategy makes it quite daunting to distinguish between the interventions set up prior to the adoption of the I4.0 strategy and those established specifically because of an I4.0-related intervention. For the sake of simplicity and comprehensiveness of the analysis, this paper limits the discussion to the single most important and elaborate instrument of Germany's I4.0 strategy, namely *Plattform Industrie 4.0*.

Additional data were drawn from evaluations conducted on Germany's I4.0 strategy, including self-assessments or other independent evaluations carried out by third party entities. The review of key findings supports the hypothesis that Germany's approach to I4.0 is better understood as a sophisticated policy learning and policy experimentation process (Cunningham et al., 2013) sustained by a complex mix of novel and existing policy interventions in interaction with the actions of a diverse set of stakeholders.

3. What I4.0 is about

The rapid and significant increase in computing power at shrinking costs has resulted in the widespread adoption of digital technologies across the economy. In manufacturing, digital technologies first spread to individual parts of the production process but is increasingly enabling the linking of multiple manufacturing processes in virtually real time. The rapid convergence of digital technologies, manufacturing processes, logistics and human systems is driving the emergence of the "Smart Factory" or "Digital Factory", which lies at the core of I4.0.

The smart factory is a production facility where the majority of tools and machines are automated –from production robots to transportation devices or additive manufacturing (also referred to as "3D-printers"). In the smart factory, the *means* of production and the *product* itself are equipped with sensors and actuators that allow them to connect with one another. They form a "cyber-physical system" (CPS, or "cyber-physical production system", CPPS), connected via the Internet of Things (IoT, or Industrial Internet of Things, IIoT, to distinguish it from networked consumer electronics like smart homes or wearables). The networked smart factory allows assigning identities to tools and machines but also to products and materials. This then makes it possible to precisely locate and keep track of items at each level of the production and supply chain. Direct communication and cooperation between humans, machines, logistics and products helps optimize production and value chains.

This networked and automated production environment is supplemented by “big data” which refers to the enormous amounts of data from millions of nodes in a network; this includes the ability to process and analyse large amounts of data using cloud computing, for example. The result is a reduction in business uncertainties, as information about changing business environments can be handled, processed and analysed in almost real time, and then passed on to the production facility directly: machines and tools will adjust operations accordingly.

Greater customization is possible while retaining speed and efficiency. Individual products are networked and identifiable; customization is feasible according to user data, and there is a direct connection from customer data to machine data. Furthermore, cloud computing and additive manufacturing allow for a decentralization of production. Information is no longer centrally stored but located directly within the product itself. Because decision-making about changes in production can be decentralized, manufacturing in I4.0 can consist of multiple, flexible and localized systems and machines with functions distributed throughout a network without a solid hierarchy.

Notwithstanding progress achieved so far, the networked manufacturing sector remains an aspiration; most existing efforts are still at pilot stages, with no single country yet being able to fully transform significant parts of its manufacturing base into I4.0. This raises questions about the scalability of I4.0, but also about the capacity of I4.0 strategies to diffuse across different sectors or countries.

4. The policy process underpinning Germany's I4.0 strategy

Germany is a pioneer in recognizing and strategically embracing the organizational and technological trends around manufacturing as drivers of development.[4] Conceived as a marketing tool (Pfeiffer, 2017), I4.0 has become a symbol of the country's determination to secure its future as one of the world's leading manufacturing hubs (Forschungsunion/acatech, 2013). It encompasses strategic measures to consolidate Germany's technological leadership in mechanical engineering and related fields:

> "As a leading supplier of industrial equipment at the global level, the digital restructuring of industry offers plenty of opportunities to boost international competitiveness of German production and better conditions for job creation." (Digital Transformation Monitor, 2017:3)

Next, we analyse the sequence of policy initiatives and processes that have paved the way for I4.0.

4.1 The beginnings: setting framework conditions for I4.0

4.1.1 High Tech Strategy (2006)

The first piece of legislation that can be linked to Germany's present I4.0 strategy was issued in 2006: the "*Hightech Strategie*" (hereafter HTS) drafted by the *Forschungsunion* and the *Expertenkommission Forschung und Innovation (*EFI, Expert Commission Research and Innovation). The HTS, dubbed "coordinated innovation policy", was launched by the German Ministry of Education and Research (BMBF) as a cross-ministerial strategy to strengthen and secure a leading position in research and innovation and as a global production hub (Digital Transformation Monitor, 2017). Comparative advantage could not hinge on lowering production costs but on outperforming competitors. Innovation should drive competitiveness and secure market advantages and growth potential, contributing to a steady stream of new products, production techniques and services (BMBF, 2006).

HTS employed several tools to achieve its intended goals. First, several cross-cutting "activities" have been pursued, including enhancing linkages between research and the private sector, improving conditions for start-ups and SME innovation, accelerating diffusion of innovative technologies, strengthening Germany's position internationally and investing in people. Second, HTS focused on fostering innovation in three areas:

[4] In 2015, Angela Merkel urged the audience at the World Economic Forum in Davos to

> "Quickly master the amalgamation of the world of the internet with the world of industrial production because the current leaders in the digital area will otherwise take over industrial production." (Schroeder, 2016:0)

- Innovations for a healthy and secure life with a focus on biotechnology, security, plants, energy and environment;
- Innovations for a communicative and mobile life targeting ICTs, logistics, space and maritime technology and services; and,
- Innovations through cross-cutting technologies which included production technologies—directly relevant for I4.0—even though the strategy still did not make use of that term at the time.

Innovations through cross-cutting technologies aimed to secure leadership in mechanical engineering and plant construction; the country was to remain the leading market ("*Leitmarkt*") for innovative production technologies. HTS advocated the networking of different stakeholders, the establishment of a platform for the promotion of sustainable innovation pathways, further adoption of nanotechnology in production, fighting against product piracy, the unleashing of SMEs' innovative capacity and increasing the attractiveness of the engineering industry (BMBF, 2006).

4.1.2 Deutschland Digital 2015 (2010)

In November 2010, BMWi introduced its first holistic strategy for Germany's digital future: *Deutschland Digital* as the framework for all ICT-related government interventions; it was business-oriented, intended to strengthen the country's position as an ICT location. It emphasized that as of 2009, the contribution of Germany's ICT industry to gross value added surpassed that of the mechanical engineering or automobile industry. BMWi proposed combining the potential of the ICT industry with other more established industries to achieve an intelligent network (BMWi, 2010). *Deutschland Digital* built on several key aspects:

- To strengthen the German economy's competitiveness through increased adoption of ICTs;
- To strengthen the digital infrastructure and grids to prepare for future challenges;
- To protect the rights of internet users when using new media;
- To expand R&D in the IT industry to accelerate innovation;
- To strengthen education and vocational training and include new digital competencies;
- To use ICTs in the quest for solutions to major societal challenges such as sustainability, climate change, health, mobility, administration and the improvement of quality of life.

Modelled after the “Digital Agenda for Europe”, *Deutschland Digital* assumed close collaboration between policy, business and research. The establishment of the national IT summit (now “Digital Summit”) was a noteworthy event in the implementation of *Deutschland Digital*. As a holistic strategy, it encompassed numerous projects in different fields, with many closely related to the future I4.0 strategy:

- “Strengthening growth, competitiveness and jobs through digitalization”: increasing the adoption of ICTs among SMEs and the importance of cloud computing and support for the development of open standards and interoperability;
- “Digital networks”: investment in ICT infrastructure and in the development of adequate legal environments;
- “Trust and security in the digital world”: data security and copyright protection;
- “R&D”: research on IoT and system integration;
- “Education and competencies”: education and vocational training and the changing nature of workplaces in the ICT environment.

Several policy interventions supported the implementation of *Deutschland Digital*, many of which had not emerged from it; rather, they had been in operation long before the programme was launched and had simply been “captured” by the new agenda. Various programmes remain in operation to date and have become an integral part of Germany’s I4.0 strategy. Among the most important projects arising from *Deutschland Digital* is the *KMU-innovativ* funding initiative, the *High-Tech Gründerfonds*, the IT-Summit, the Trusted Cloud funding programme, the broadband strategy, the *Autonomik 4.0* programme and the Connected Living programme.

4.1.3 High-Tech Strategy 2020 (2010)

In 2010, BMUB published an update of the HTS entitled “*Hightech Strategie 2020*”, which focused less on specific technologies and more on concrete solutions to global challenges. The *Forschungsunion* introduced five key terms—climate and energy; health and food; mobility; security; and communication—and associated cross-cutting interventions to improve framework conditions, equally benefiting all five key areas (BMBF, 2010):

- Improving the environment for start-ups, particularly to increase the number of spin-offs linked to higher education organizations. Improving framework conditions for the operation of young tech companies;
- Supporting SMEs to enhance innovative capacity by fostering networking between SMEs and the research sector. The strengthening of two instruments, the “Central

Innovation Programme SMEs" (ZIM) and the funding initiative "SMEs innovative" was expected to contribute to these goals;

- Strengthening the framework conditions to improve venture capital markets in Germany;
- Standardization as an integral part of the research and innovation process to improve the transition from research to the market. Private sector actors should contribute to progress in standardization;
- Innovation targeting public procurement was considered an effective tool to strengthen innovation and increase public sector efficiency;
- Vocational training and university education should help secure the supply of skilled labour. A government supported "qualification initiative" aimed to promote education, especially in engineering.

In addition to these cross-cutting interventions, targeted actions within each of the five key areas were considered. Although these strategic initiatives still made no reference to I4.0, some of their proposed actions under "communication" deserve mention (BMBF, 2010):

- The German government pledged to develop an ICT strategy by 2010, including the organization of an IT-summit (see preceding discussion on *Deutschland Digital*);
- Cooperation with research entities to set up an ICT action programme on cloud computing (development, testing, security and standards);
- Intensify research and the promotion of "smart objects" with an emphasis on service robots for industry;
- Elaborate a national roadmap for embedded systems and IoT, engaging diverse stakeholders and sectors;
- Development and upgrading of communication infrastructure;
- Elaboration of an ICT skills development programme targeting SMEs and updating the curricula in vocational training and at universities.

The implementation of the five key areas required distinct "*Zukunftsprojekte*" ("future strategic initiatives") to tackle concrete scientific and technological development goals over a period of ten to 15 years. These strategic initiatives aimed to systematize problem-solving, had precisely defined targets and provided the foundation to develop "roadmaps". However, their implementation was only possible upon adoption of the ensuing "action plan"; it is in this publication where the designation 'Industry 4.0' first appeared (BMBF, 2012).

4.2 I4.0 enters the public domain

4.2.1 Action Plan HTS 2020 (2012)

The German government, together with the *Forschungsunion*, developed ten strategic initiatives linked to the five priority areas of the 2010 HTS. The ten initiatives highlighted the need for cooperation among German innovation-related stakeholders. The German government planned to invest EUR 27 billion in the implementation of these strategic initiatives over the 2010-2013 period (BMBF, 2012:7).

The *Forschungsunion* adopted the *Promotorengruppen* ("Promotions Groups") for each key area of the HTS 2010. The Groups were chaired by research and industry representatives. In early 2011, the "Promotion Group Communication" proposed the term "*Industrie 4.0*" to the German government to identify a project of the future. I4.0 was subsequently introduced at the same year's Hannover Trade Fair by representatives of *Acatech, BMUB* and *DFKI*. Later, I4.0 was included in the 2012 "Action Plan High-Tech Strategy 2020" and became one of the ten "strategic initiatives" of the 2010 HTS.

The strategic initiative *Industrie* 4.0 focused on technology policy, economic policy and social policy. It included existing programmes such as the IT Summit, the National Roadmap Embedded Systems, *Germany Digital 2015* or the *AUTONOMIK* strategy, increasing those programmes' I4.0 focus. BMBF's new research agenda targeted "smart factories", "embedded systems", IoT and "virtual reality". Research was to increasingly be carried out in partnership with the private sector. BMWi also pledged to bolster I4.0 projects, especially in "smart production", "human-machine interaction" and "3D". These projects aimed to target SMEs in particular.

The action plan assumed increased engagement of the business and research communities, especially in production technology and mechanical engineering. The significance of "living labs" and "testbeds" was also emphasized. The action plan furthermore promoted the creation of a working council I4.0 to coordinate activities and summarize recommendations regarding the transition to I4.0. Investments in the order of EUR 200 million was pledged to support the strategic initiative I4.0 (BMBF, 2012).

Subsequently, an I4.0 Working Group within the *Forschungsunion* developed a preliminary strategy— published in October 2012—with recommendations for its implementation. These recommendations introduced one of the central tenets of Germany's future I4.0 strategy: the dual goal of becoming both the leading supplier of and leading market for I4.0.

- Becoming a leading I4.0 supplier meant strengthening German industries supplying I4.0 technologies, specifically mechanical engineering, automation and ICTs. This process entailed (i) expanding on existing market advantages, especially in production technology; and, (ii) significant investments in research and innovation and increasing qualifications in the fields of automation and AI, technical infrastructure and novel approaches to labour organization. Moreover, the aim was to enforce intellectual property rights, impede product piracy and develop new business models;
- Becoming a leading market for I4.0 meant large-scale deployment of I4.0 technology in German production chains including MNCs and SMEs. The basis for this was profound knowledge and a technology transfer within the German market across sectors and company sizes. Becoming a leading market, however, also required the development of the appropriate digital infrastructure.

(BMBF, 2012) also provided for specific kick-off activities: developing technology roadmaps and coordinating their implementation, promoting research, ensuring training and skills upgrading, pursuing internationalization, establishing I4.0 competence centres, creating an I4.0 community and setting up demonstration factories.

In 2013, again at the Hannover Trade Fair, the I4.0 working group published an updated version of its final report with recommendations for the implementation of I4.0 (Kagermann, Wahlster and Helbig, 2013). This time, *Acatech* joined the *Forschungsunion*. The report expanded on the 2012 recommendations and proposed eight fields of intervention:

- Standardization and open standards for a reference architecture
- Managing complex systems
- Delivering a comprehensive broadband infrastructure for industry
- Safety and security as critical factors for the success of I4.0
- Work organization and work design in the digital industrial age
- Training and continuing professional development for I4.0
- Regulatory framework
- Resource efficiency.

These recommendations for implementation were circulated more widely than the report that mentioned '*Industrie 4.0*' for the first time. It is this second report that is often cited as providing *the* definition of I4.0 as a new type of industrialization built on an evolutionary process which, if successful, will assist Germany in preserving domestic manufacturing and increasing global competitiveness (Kagermann, Wahlster and Helbig, 2013). These two reports helped institutionalize I4.0. In 2011, the setting up of "*Plattform Industrie 4.0*" (PI4.0) marked the continuation of the working group I4.0's work. The Plattform was an initiative of the three industry associations *BITKOM*, *VDMA* and *ZVEI*, consulted by *Acatech*. It later became a defining feature of Germany's I4.0 strategy.

4.3 I4.0 and the future of manufacturing

4.3.1 Digitale Agenda 2014-2017 (2014)

The concept of I4.0 has rapidly gained popularity, featuring prominently in multiple policy strategies – including the 2014 "*Digitale Agenda*" (DA), implemented by BMWi, BMI and BMVI. The DA set out to tap into the digitization of Germany's economy to foster an innovative economy, a competitive service society and an industrial nation (Die Bundesregierung, 2014b). The ICT sector would offer both business and investment opportunities and be a driver of innovation, productivity, sustainable growth, prosperity and employment (Die Bundesregierung, 2014b). The DA promoted three core strategic objectives: 1) growth and employment, 2) access and participation, and 3) confidence and security.

The DA advocated for a networked economy to recast value chains and transform business models in Germany's leading industries, namely plant and mechanical engineering, car manufacturing, electrical and medical engineering. Germany aspired to be Europe's leading digital economy through the development of commercially viable and reliable technologies, becoming a benchmark for digital applications, including in smart production and logistics. The *Mittelstand* (small and medium-sized enterprises) was identified as a priority sector whose transition towards the digital economy should be supported. Target areas included improvements in innovation capacity and the optimization of business processes through adoption and/or development of new digital technologies and the promotion of business start-ups (Die Bundesregierung, 2014b). The DA included broad recommendations only, resorting to advocating concrete measures to achieve these ambitious goals.

4.3.2 HTS Update (2014)

A final update to the HTS was published in 2014, this time coordinated by the German Federal Government itself and not through one of its ministries. The update reiterated Germany's commitment to leadership in global innovation and to strengthening its status as a leading industrial and exporting nation (Die Bundesregierung, 2014a). Compared to the 2006 and 2010 HTSs, the 2014 update placed greater emphasis on involving civil society. The consulting body of the German government was expanded to include the research union, a traditional partner, but also the *Hightech-Forum* which consulted the government until 2017 (Hightech-Forum, 2018).

Similar to the 2010 update, the 2014 HTS focused on five core elements with several associated priority tasks: (i) value creation and quality of life (to enhance competitiveness and increase prosperity); (ii) better networking and transfer (to strengthen cooperation and support implementation); (iii) enhanced innovation dynamism (to strengthen innovation capacity and value creation); (iv) improved framework conditions (to provide the basis for creativity and innovation); and (v) intensified dialogue, transparency and participation (to stimulate curiosity and promote forward-thinking) (Die Bundesregierung, 2014a). The implementation of the 2014 HTS rested on five pillars:

(1) Concrete "forward-looking projects" (re-branded "strategic initiatives"), which entailed the priority tasks;
(2) New instruments to improve knowledge transfer between research and business with a regional focus;
(3) Enhanced innovation dynamic targeting SMEs and technology-based entrepreneurs in particular;
(4) Improved framework conditions (education and training, financing and legal environment); and,
(5) Increased dialogue between all stakeholders and fostering civil society participation.

The "forward-looking projects" sought to translate the core pillars into concrete deliverables; I4.0 was, for the first time, a component of the HTS. The core element "value creation and quality of life" encompassed the project "digital economy and society" with the key "field of action" being I4.0. The government's goal was to support research and businesses in implementing I4.0, while considering IT security and the aim of becoming a leading supplier and leading market for I4.0. The update called for an assessment of possible implications of I4.0 on jobs and the need to protect the interests of both employers and employees (Die Bundesregierung, 2014a).

Additional "fields of action" in the forward-looking project "digital economy and society" included smart services, smart data, cloud computing, digital networking, digital research, digital education and digital livelihoods, all of which can be associated with I4.0.

5. Learning and experimentation

5.1 From implementation of an ambitious innovation policy to the emergence of I4.0

Germany's I4.0 strategy is often described as a "dual approach" to become both the most important market for I4.0 and the lead supplier of I4.0 solutions in the world (Digital Transformation Monitor, 2017). Such a depiction seems to overlook the fact that I4.0 emerged from a larger policy and that it has been implemented through multiple government agencies and ministries, requiring priority setting, comprehensive coordination and collaboration. In addition to BMBF, which has a mandate to support research and implementation of the action plan (BMBF, 2018), and BMWi, which has a mandate to support research, standardization and regulation (BMWi, 2018a), several other ministries contribute to policymaking and policy implementation (Table 1).

Table 1 German ministries directly involved in I4.0

Ministry	Areas
Federal Ministry for Economic Affairs and Energy	Industry support, unions and platforms
Federal Ministry of Education and Research	Research support
Federal Ministry of Labour and Social Affairs	Employment, qualification
Federal Ministry of the Interior	Data security
Federal Ministry of Transport and Digital Infrastructure	Infrastructure, broadband wiring
Federal Ministry of Justice and Consumer Protection	Consumer protection, data security

Source: Taken from Schroeder (2016)

The discussion in Section 4 suggests two things: first, that I4.0 is part of a larger development puzzle whose solution involves diverse stakeholders. Second, the strategic build-up towards I4.0 has been neither static nor linear; the process is best characterized as one of experimentation, learning and continuous fine-tuning. Already in the self-description of the 2015 *Umsetzungsstrategie*, the "dual strategy" was presented as part of a broader and more complex innovation and development strategy. Policy design and implementation have undergone cycles of monitoring and feedback loops that support the improvement of quality and efficiency of public interventions (OECD, 2014).

Germany's I4.0 emerged from a complex and evolving innovation policy mix under the HTS strategy which has undergone a sequence of updates since its adoption in 2006 (Reischauer, 2018; Pfeiffer, 2017). Although I4.0 has become the "central" component of the HTS, it was conceived as one of ten "forward-looking projects" proposed in its latest update (2014) (BMWi, 2014). I4.0 was embedded in the first core element, namely value creation and quality of life (digital economy and society, sustainable economy and energy, innovative workplace, healthy living, intelligent mobility and civil security).

The German HTS illustrates what Cunningham et al. describe as a high-level policy mix that involves all layers of policymaking in one space over time (Cunningham et al., 2013). It is an example of:

> "The design of a cross-government mix based on a unifying strategic vision which is institutionalised over time; not through creating new agencies or centralising its implementation, but through the bundling of existing activities, the subsequent design of new and complementary instruments implemented by diverse agencies and ministries with their own budgets, and monitored and supported by an accompanying evaluation." (Cunningham et al., 2013:V)

5.2 The policy learning and policy experimentation process

In experimental innovation policy, organizations focus their attention on measuring performance. For this exercise to be useful, the right indicators need to be defined and measured in the right way. Organizations need to thus determine the factors that influence performance, determine the root causes of any deficiencies and take appropriate action. They also need to consider a broad range of indicators that are difficult to measure. Diagnostic monitoring and adjustments to policy direction are important for determining the scope of experimental policy. The novelty of I4.0 means that its true nature and the full scope and scale of its implications is ambiguous. This usually requires experimentation with a large scope to learn and identify good practice.

The DA's foreword acknowledges that its implementation is an open ended process, inclusive of all relevant groups in German society and that it requires continuous development and adjustments through extensive dialogue (Die Bundesregierung, 2014b). I40 entails cross-sectoral approaches and has benefited from a long-term vision and a gradual implementation process (Digital Transformation Monitor, 2017). Policymaking has capitalized on past experiences; for example, on efforts to extend membership, common norms and standards within networks to reduce competition; on the provision of targeted funding instruments and testbeds; or, on the inclusion of specialized support for SMEs to endorse I4.0 and enter global value chains (Digital Transformation Monitor, 2017).

The experimental nature of Germany's I4.0 policy is evident from the research-oriented nature and the roles played by the three agencies most heavily involved in its drafting, evaluation and update (Box 1). These agencies have promoted continuous dialogue, analytical work and discussions among distinct stakeholders – government, academia, industry and other interest groups. Many of the consulting bodies responsible for drafting the I4.0 strategy have close links to the private sector. The *Forschungsunion* consists of representatives from business and research and is chaired by the Fraunhofer Institute. The head of the communication promotion group in charge of developing the I4.0 concept is a former SAP manager. The majority of *Acatech* executive board members are representatives of large MNCs.

The I4.0 strategy features agenda-setting mechanisms, visionary and top-down supervisory roles for the government (through BMBF and BMWi) and ambitious funding strategies and investment commitments (Digital Transformation Monitor, 2017). While emphasis is put on collaboration and partnership-building, industry, science and the social partners are responsible for developing strategic orientations and for implementing measures in collaboration with policymakers (Digital Transformation Monitor, 2017). Thus, one feature of Germany's innovation policy and its I4.0 strategy more specifically is the active engagement of non-governmental stakeholders in distinct phases of policymaking and implementation.

Box 1 Entities underpinning policymaking and policy learning and experimentation around I4.0

- *Forschungsunion Wirtschaft-Wissenschaft*

From 2006-2013, the HTS was developed in close collaboration with the "*Forschungsunion Wirtschaft-Wissenschaft*" ("Industry-Science Research Alliance"). BMBF set up the research alliance to serve as the core advisory body for innovation policy in Germany. It contributed to innovation policy drafting over a period of seven years. The alliance comprised several *Promotorengruppen* ("Promoters Groups") responsible for proposing "strategic initiatives" to implement different policy strategies. The groups promoted dialogue around these issues and identified drivers and obstacles to the implementation process. The research alliance consisted of 28 representatives from business and research.

- *Expertenkommission Forschung und Innovation (EFI, Expert Commission Research and Innovation)*

The EFI comprises six members from research and academia and is fully funded by BMBF. It was established by the German government in August 2006 with a mandate to publish regular updates on research and innovation in Germany, including changes in the country's technological capabilities. The first such report was published in 2008. In elaborating these reports, the EFI carries out annual assessments of the strengths and weaknesses of Germany's innovation system, considering both the national and international context. These reports inform EFI's recommendations to improve national research and innovation policy.

- *The German Academy of Technical Sciences (Acatech)*

Acatech, short for *Deutsche Akademie der Technikwissenschaften* (German National Academy of Science and Engineering) is a publicly funded academy representing the interests of German technical sciences. It emerged from the "Convent for Technical Sciences" founded in 1997. *Acatech* advises politicians and the public on all issues relating to technical sciences and technology policy through publications, symposia, workshops or panel discussions. It aims to promote knowledge transfer between science and business and to promote sustainable growth through innovation. *Acatech* collaborated with the *Forschungsunion* in drafting the first HTS and was heavily involved in the development of I4.0 and the recommendations for its implementation.

The institution consists of a general assembly, a senate and an executive board, which includes representatives from Fraunhofer, Siemens, Munich RE, Daimler and several research-intensive German universities, among others. *Acatech* is advised by the senate on strategic matters. Its members are CEOs and chairmen of major technological corporations, presidents of the main science organizations in Germany and policy representatives.

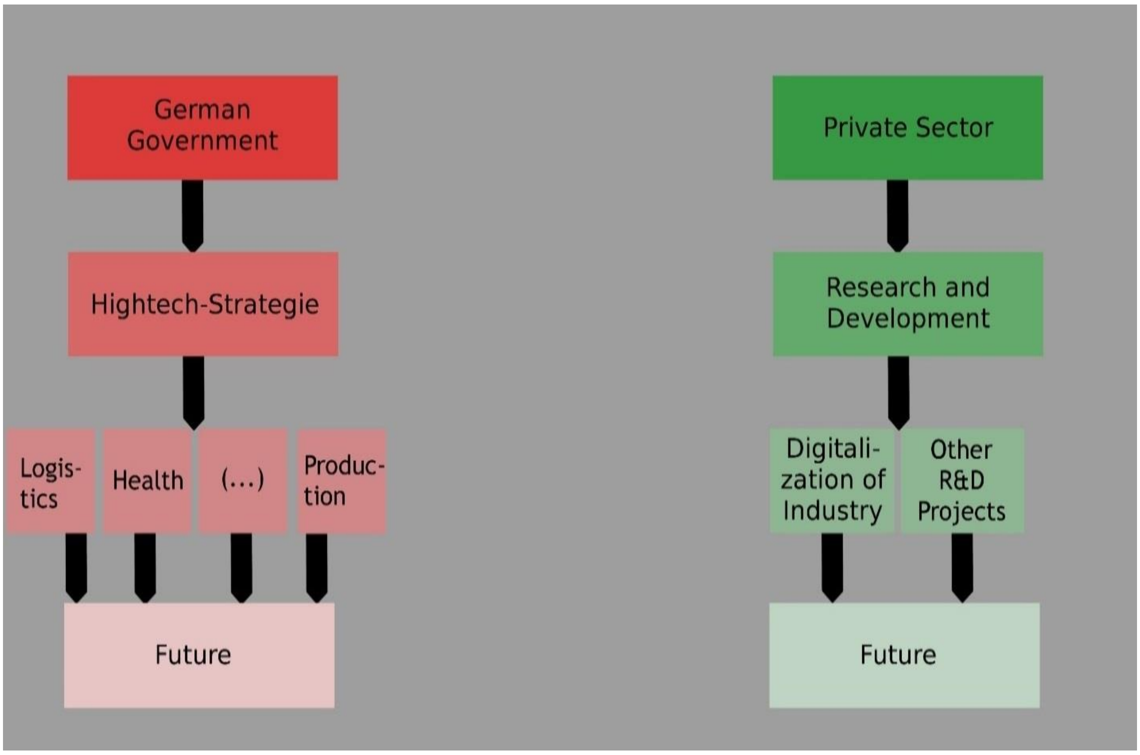
Policy learning is not just about leveraging knowledge from previous experience with implementing policy instruments, but from being open to learning from the complementary actions of other agents (Cunningham et al., 2013; Flanagan, Uyarra and Laranja, 2011). Germany's I4.0 strategy consists of projects that are or were neither initiated nor funded by the German government. Responsibility to implement those projects lied with universities, public and private research institutes and private sector companies of all sizes; the German government actively promotes I4.0, especially among SMEs. Concrete interventions have included:

- PI4.0 set up by the industry associations *BITKOM*, *VDMA* and *ZVEI* without any government support and was only later "captured" by BMWi and BMBF;
- Most of the successful displays of I4.0 technologies were organized on private sector initiative, for example, the Siemens Amberg Factory, the Bosch Blaichach Factory, the Festo Scharnhausen Factory and the Pepperl&Fuchs Solutions Park;
- Interventions targeting vocational training and higher education programmes around I4.0-related competencies and consultancy have almost exclusively been carried out by non-governmental stakeholders, for example, the Bosch Rexroth Drive & Control Academy, Festo with its "Didactic" programme; or ZEISS' "Curriculum4.0".

The private sector contributes considerably to planning and design, as well as to actual implementation in collaboration with policymakers. In the early days of I4.0, private organizations dominated in leading I4.0 initiatives while the government only joined later by tapping into previous private sector efforts. Figure 1 , Figure 2 and Figure 3 illustrate the evolution of public-private collaboration.

In the early stage of the development of I4.0, the German government sought to foster innovation as the foundation for the future performance of the country's economy and to secure its leading position in the global scene (Figure 1). At the same time, private companies were engaged in digitalization processes and undertook significant R&D efforts. None of these processes focused exclusively on I4.0.

Figure 1 **Independent innovation circles in the public and private sector**



Over time, the proximity of public and private sector innovation efforts eventually led to cross-fertilization processes (Figure 2). The *Forschungsunion* and *Acatech* positioned themselves as strategic intermediaries partly because of the strong presence of industry representatives in key senior management positions within the two organizations, and partly because of their role as consultative bodies to the government. This is when I4.0 was adopted by private sector organizations.

Figure 2 **Government and private sector efforts to become involved in the other's activities and innovation agendas**

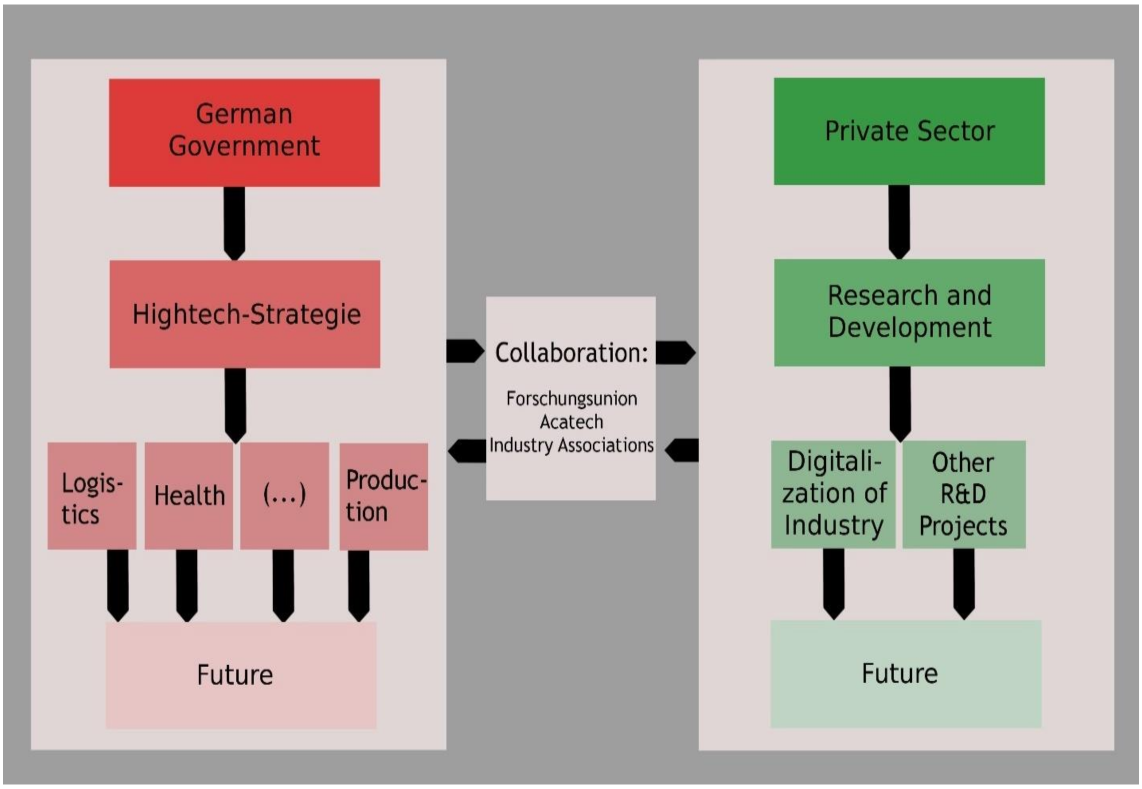
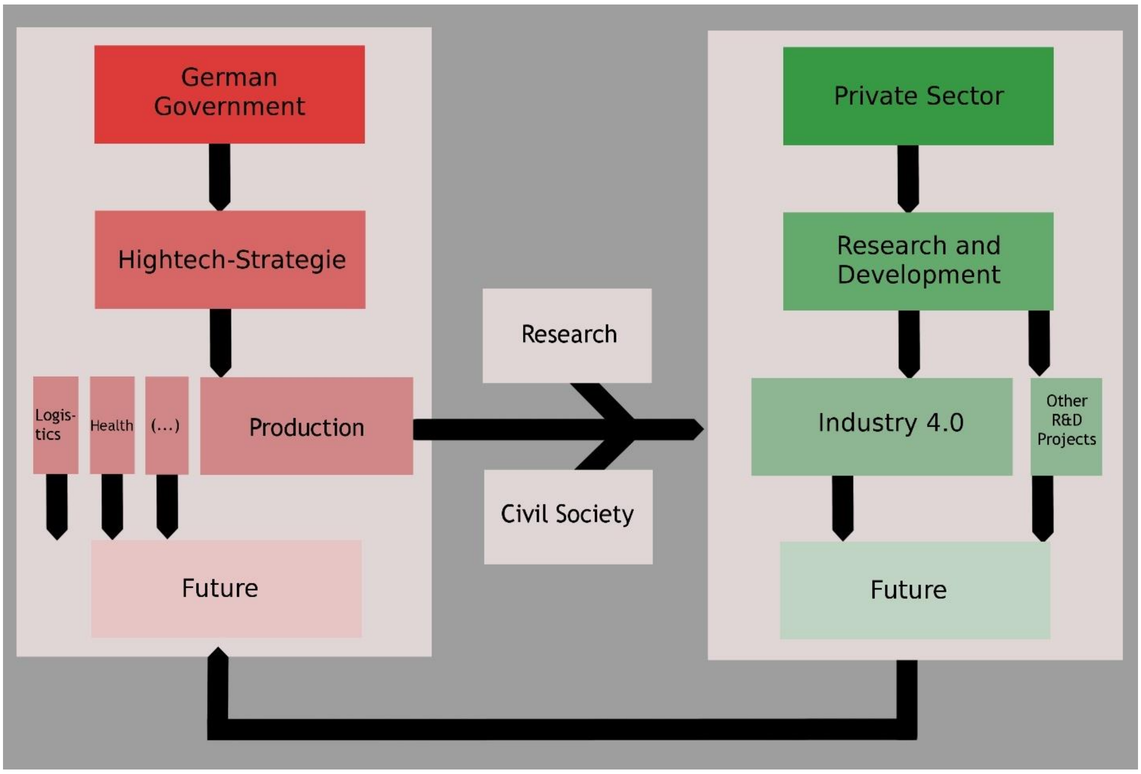


Figure 3 shows how the government eventually 'captured' the private sector's efforts (mainly PI4.0, SCI4.0 and LNI4.0), while encouraging research and civil society to participate and contribute to the achievement of I4.0-related objectives.

Figure 3 **Public-private collaboration within Germany's I4.0 strategy**



Policy evaluation significantly contributes to policy learning, with different learners being expected to take different approaches to evaluation and to learn a number of things through various mechanisms (Borrás and Højlund, 2015; Patton, 2008). Despite its novelty, Germany's I4.0 strategy is already being queried for influence—and even impact—on the performance of various agents, from firms or industries to the economic system (Box 2). Evaluations have been conducted by government and non-governmental entities, although assessments carried out by non-governmental organizations tend to focus on the readiness of a specific company or industry for I4.0 (e.g. (World Economic Forum, 2017; 2018)), while the evaluation of government I4.0 policies remains secondary for this type of studies. Further and more systematic research is needed to better substantiate objective conclusions, while firm-based studies remain difficult to compare due to methodological and sampling differences. Despite these shortcomings, the emerging evidence suggests positive influences from I4.0 on the German economy's performance and the manufacturing sector more specifically.

Box 2 How successful is Germany's approach to I4.0?

Policy influence

(Kagermann et al., 2016) acknowledge the influence and uptake Germany's I4.0 strategy has had on innovation policy both in Germany and other countries. (Pfeiffer, 2017) and (Kagermann et al., 2016) assert that the diffusion of I4.0 has benefited from the concerted efforts of businesses, trade unions, industry and research associations, academia and government. Diverse German organizations contribute to the conceptualization and implementation of I4.0, including through pilot smart and learning factories.

Uptake of I4.0

According to (Heilmann, Eickemeyer and Kleibrink, 2016) as of 2016, the adoption of I4.0 remained limited to a select group of pioneering companies in Germany. Similarly, (Pierre Audoin Consultants GmbH, 2015) contend that only 15 per cent of surveyed companies use decentralized, self-controlled systems in any part of their production line. In mechanical engineering, this figure was 9 per cent, whereas in the automotive industry, it was 18 per cent. Along similar lines, (Milojevic and Lörcher, 2017) argue that 54 per cent of German companies fail to use any sort of IoT or similar data gathering technologies to optimize production processes. In general, German companies are reluctant to use such applications for connected product applications; sensitive data protection and privacy issues stand out among the reasons explaining such behaviour (Milojevic and Lörcher, 2017).

Economic performance

(Holz, 2017) presents evidence of growth in all of Germany's I4.0-related industries. Between 2016 and 2017, hardware solutions grew by over 14 per cent, software solutions rose by 23 per cent and IT services by 22 per cent. In contrast, the obstacles associated with the application of I4.0 solutions included high investment costs, issues related to data protection and data security, and the dearth of skilled workers. Holz recommended investing in improved skills and training, pilot projects and in establishing I4.0 hubs.

(Blanchet, Rinn and, Dujin 2016) conclude that Germany is the only country where the transition to I4.0 has been accompanied by significant improvements in the return on capital employed (ROCE) over the last 15 years. Despite a slight drop in employment (9 per cent), value added grew by 80 per cent between 2000 and 2014, while profits increased by 158 per cent. Investments and depreciation remained stable over the same period, with a more efficient use of assets. The rate of use of production equipment grew from 85 per cent in 1998 to 95 per cent in 2014. As a result, Germany's ROCE climbed from 12 per cent in 2000 to over 30 per cent in 2014 (Blanchet, Rinn and Dujin, 2016).

In a recent study on the digitalization of SMEs and the innovative capacity of the German economy, (Saam, Viette and Schiel, 2016) conclude that only 21 per cent of all enterprises in their study used digital technologies in production. However, the use of technologies such as big data analysis, exceeded expectations. In contrast, (Von Kai, 2017) finds that annual German GDP growth could increase by another 0.3 percentage points if SMEs used I4.0 solutions more consistently. Low I4.0 penetration among SMEs could be explained by the dearth of skilled employees—qualified IT personnel for new digital projects—rather than a lack of funding or innovative capacity. Moreover, many SMEs find it difficult to fully grasp the scope of change that I4.0 and the increased use of IT might bring in terms of productivity growth.

I4.0-enabling interventions

Progress reports published by Platform I4.0 (BMWi, 2016b) indicate that the working group on "Reference Architectures, Standards, and Norms" has published the RAMI4.0 model and certified it as a DIN specification[5] (Platform Industrie 4.0, 2016b). The working group on "Research and Innovation" has proposed a research roadmap, including on obstacles to innovation (Platform Industrie 4.0, 2014), and scenarios for the future development of I4.0-related technologies (BMWi, 2016a). The founding of the LNI4.0 as a contact point for users on the implementation side of the PI4.0 stemmed from activities of this working group (LNI4.0, 2016). The working group on "Security of Networked Systems" has published a guide specifically targeting SMEs' security (Platform Industrie 4.0, 2016a). The working group on "Legal Framework" published some of its research results in separate papers. Finally, the working group on "Work, Education and Training" published recommendations in close consultation with employee representatives (Plattform Industrie 4.0, 2016).

(BMWi, 2016b) documents several successful initiatives managed through PI4.0, including a map showcasing I4.0 examples, the I4.0 competence centres (coordinated through PI4.0) or the implementation of the internationalization strategy and the adoption of several bilateral agreements on research collaboration with developed countries in particular. The document concludes that "with over 250 participants from more than 100 companies and organizations, Plattform Industrie 4.0 is nationally and internationally one of the largest and most diverse Industrie 4.0 networks." (BMWi, 2016b:20)

(Probst et al., 2017) assert that despite the availability of high-quality digital infrastructure in Germany, the country's score for industrial and enterprise digitization is low relative to that of other countries. Performance in ICT start-ups is poor when compared to other dimensions of digital transformation, and Germany scores low in the entrepreneurial culture dimension.

[5] Deutsches Institut für Normung e.V. (German Institute for Standardization)

Evaluation has helped identify gaps in the design and implementation of the I4.0 strategy. For instance, (Kagermann et al., 2016) urged German policymakers to more actively pursue the internationalization of the strategy; international networking should enable the dissemination of I4.0 among businesses. The authors decried the slow pace of adoption of I4.0-compliant standards in Germany relative to other countries. In their view, an active top-down policy approach to promote norms and standardization could contribute to a common international infrastructure within a relatively short time, thereby boosting Germany's competitiveness over the medium term. (Santiago, 2018) documents that German firms are actively sought by partners in developing countries to assist them in the development of their national or individual I4.0 strategies, although those activities seem to remain outside the scope of major German international development sponsors.

The complexity and the very technical understanding of I4.0 is an obstacle to its success; potential adopters, particularly SMEs, (Von Kai, 2017), have a difficult time endorsing it (Holz, 2017). Moreover, the bias towards mechanical engineering and automation suggests a policy-capture process stemming from the significant contribution made by private entities, particularly large multinational companies of German origin (Box 3).

6. *Plattform Industrie* 4.0 and its contribution to Germany's I4.0 strategy

Section 4 traced the policy process underpinning Germany's I4.0 strategy. Each stage of the policy process was accompanied by the adoption of a wide array of policy instruments. As discussed throughout this paper, the diversity of policy instruments and the fact that many of those already in place were seized to serve the ends of each update of the HTS policy makes their systematic analysis fairly problematic. The instruments that can be linked to I4.0 have evolved over time. From very generic regulatory, financial and soft interventions targeting improved framework conditions for innovation—with Germany's HTS as a framework—they have become increasingly focused on fostering concrete technologies, activities or areas linked to I4.0. It is in this last set that one can include the PI4.0, the Standardization Council and the Labs Network. Figure 4 provides a simple illustration of this. Next, we discuss PI4.0 in more detail.

Figure 4 **The policy process of Germany's industry 4.0 strategy**

Box 3 Germany’s specialized approach to I4.0: a double-edge sword

Germany’s approach to I4.0 is often criticized for its emphasis on mechanical engineering and automation and smart factories (Probst et al., 2017). These areas are central for Germany’s comparative advantage, especially as regards CPPS, IoT, AI, transport and automation (Probst et al., 2017; Bitkom, 2016). However, the development of those areas often curtails attention to others with strong potential for value creation, for example “platformization” (Probst et al., 2017). (Expertenkommission Forschung und Innovation, 2017) note the HTS’ failure to horizontally connect different projects of the future, while the development of new business models and services—particularly digital business models—related to data-driven, networked applications remains more limited (Bitkom, 2016).

(Bitkom, 2016) concludes that I4.0 has developed along a single pillar; the true potential of the process has yet materialized. (López-Gómez et al., 2017) support this view, noting that Germany is currently only exploiting two out of four possible sources of value capture opportunities that can be linked to I4.0:

- Adoption of I4.0 systems (capturing value from greater efficiency, flexibility, speed/responsiveness, precision and customization)
- Manufacturing of key technology elements for I4.0 (earn revenues from key technology elements (embedded systems, robots, etc.)).

Two insufficiently exploited dimensions are:

- Building infrastructure (capturing value from growing markets providing sensors, batteries, broadband infrastructure and other technologies that underpin I4.0).
- Knowledge management and analysis (capturing value from selling tools or services enabled via the IoT).

6.1 Plattform Industrie 4.0

PI4.0 started as an industry-only initiative, and was set up by the industry associations BITKOM, VDMA and ZVEI in 2013 to continue the work of the *Forschungsunion’s* Working Group I4.0. Partners included ABB, Bosch, Telekom, FESTO, Hewlett-Packard, IBM, Infineon, Phoenix Contact, SAP, Siemens, ThyssenKrupp, Trumpf, Volkswagen and Wittenstein. The secretariat was chaired by VDMA, located at ZVEI in Frankfurt and virtually represented by BITKOM. PI4.0 was officially launched at the Hannover Fair 2013.

In its original form, PI4.0 encompassed four working groups: (1) strategy and framework, (2) reference architecture, standardization and norming, (3) research and innovation, and (4) security of networked systems. In short, the platform was a mechanism for the implementation and coordination of I40. The secretariat was mandated to:

- Work with the working groups in achieving the intended goals;
- Function as a focal point for interested companies, institutions, policy agents and the public;
- Carry out public relations through fairs, conferences, publications;
- Networking internally and with other initiatives, and community building;
- Set up and maintaining a shared information portal.

As I4.0 and PI4.0 began gaining importance, other stakeholders wanted to join. Although the government had initially refrained from joining, it eventually decided to participate and to expand the group to improve coordination, collaboration and uptake. While the business associations continued to run the platform, BMWI and BMBF assumed an increasingly active role in its development; they provided meaningful political leadership and contributed to agenda-setting. Although the platform mainly relies on voluntary activities, BMBF and BMWI have jointly allocated EUR 200 million in funding. The main office is the single entity that receives funding (Digital Transformation Monitor, 2017).

Today, PI4.0 consists of five working groups: (1) Reference Architecture, Standards and Standardization; (2) Research and Innovation; (3) Security of Networked Systems; (4) Legal Framework Conditions; and (5) Education and Training. These working groups are governed by a steering committee chaired by business representatives. The entire platform is managed by a strategy council whose members come from policy organizations, industry associations, labour unions and research organizations. In addition, a scientific council consults the group. The platform serves as a contact point for policymakers and as a bridge between industry, science and policymakers, facilitating coordination, knowledge sharing, technology and innovation (Digital Transformation Monitor, 2017). In practice, PI4.0 focuses its efforts on:

(1) Offering a platform to promote networking and learning by interested private sector stakeholders. For example, it grants partners access to literature and knowledge about I4.0. The task is supported through a showcase of best practices around I4.0 applications. PI4.0 also coordinates the work of LNI4.0.
(2) Mediating and coordinating the standardization process. The RAMI4.0 project is embedded within PI4.0. The platform also facilitates coordination between RAMI4.0

and the Standardization Council through, for example, the publication of updates on progress in the standardization process and the results.

(3) Supporting the internationalization strategy; it is the body responsible for signing cooperation agreements and facilitating access for German organizations to participate in I4.0 efforts. PI4.0 further promotes the concept of I4.0 with roadshows abroad.

In summary, IP4.0 has been the mechanism used to coordinate collective action of different interest groups involved in shaping Germany's I4.0 Strategy (Reischauer, 2018).

7. Concluding remarks

Policymakers interested in fostering national I4.0 strategies draw inspiration from Germany's pioneering experience. However, few countries, particularly developing countries, possess a comparable foundation of accumulated technological and manufacturing capabilities required to emulate such an ambitious process. Our analysis coincides with recent contributions to the literature by showing how deeply the emergence of I4.0 in Germany is rooted in its recent manufacturing development path (Schroeder, 2016; Pfeiffer, 2017). This paper has shed light on the actors, the relationships and the motivations guiding Germany's response to the Fourth Industrial Revolution.

One relevant feature of Germany's I4.0 strategy is that its starting point was, and remains, the absence of a precisely formulated I4.0 policy. It consists of a multitude of policies and projects within a larger development framework driven by innovation and coordinated efforts and contributions from distinct stakeholders (Digital Transformation Monitor, 2017). Recently, Germany has been leading development efforts to align and strengthen the country's contribution to the UN Sustainable Development Goals and the Agenda 2030 with expected impacts on the achievement of SDG9 in particular – "Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation" (Khurana et al., 2018).

The constellation of policy interventions underpinning Germany's I4.0 makes it difficult to analyse and characterize, even more so because the promotion of I4.0 has never been an end in itself, but to secure the country's position as an internationally competitive manufacturing hub. Germany's I4.0 strategy is an example of a functional innovation policy in which public interventions to support innovation are often not labelled as innovation policy (Edler et al., 2016). The search for a higher order policy goal entails a logical causality chain from policy to innovation and from innovation to the achievement of specific development outcomes (Borrás and Edquist, 2013; Edler et al., 2016).

The discussion is also consistent with views of innovation policy as a multidimensional process: several policy goals and instruments combine and co-evolve over time, nurturing overlapping relationships and feedback loops to and from other policy domains (Metcalfe, 1995; Borrás and Edquist, 2013; Lundvall and Borrás, 2004). Innovation policymaking is complex as new policy interventions are prone to creating synergies with already existing interventions; the latter are also part of the framework in which new policy goals are set (Cunningham et al., 2013). Such synergetic relationships influence not only the intensity and direction of innovation, but also the adjustments to the innovation policy and strategy to succeed (Borrás and Højlund, 2015; Borrás and Edquist, 2013).

The uncertainty surrounding I4.0 means that trial and error is the foundation for incremental and cumulative policymaking processes validated through close monitoring and continuous adjustment over time (Metcalfe, 1995; Hoppmann, Huenteler and Girod, 2014). I4.0 emerged as a concept that has helped amalgamate otherwise seemingly isolated innovation and development efforts.

It is possible to derive four key considerations for policymakers interested in drawing inspiration from Germany's I4.0 strategy:

First, the societal transformations frequently associated with I4.0 call for comprehensive policy design and implementation. From the very beginning, the German I4.0 strategy has been embedded in various other development frameworks, most notably the HTS 2006 and subsequent updates. Each update resulted in refinements to the strategy. German policymakers have been able to tap into and benefit from a development dynamic initiated and largely driven by private sector organizations. At the same time, I4.0 has been coordinated with the actions of other academic and government organizations.

Second, Germany's I4.0 strategy is not a coherent strategy designed as a holistic intervention from start to finish. It is a complex innovation policy mix characterized by a continuous policy experimentation process; cumulative learning has been sustained for a period of over a decade or so. The establishment of relevant coordination and knowledge-sharing mechanisms—notably PI4.0—has contributed significantly to the success and uptake of the model elsewhere.[6] Several policy instruments were in operation long before the formal adoption of I4.0, often targeting goals other than those currently identified with I4.0. A careful process of learning and leveraging from such interventions has substantively contributed to the strategy's success.

[6] (Schroeder 2016) documents the creation of similar platforms in other developed countries.

Third, this paper suggests that simply copying Germany's I4.0 strategy or its instruments may not provide the desired results in other countries. Policymakers should keep in mind that the required I4.0 policy development process will require long-term commitment of resources and will need to be specifically designed to suit the given country's situation. In the specific case of Germany, the I4.0 strategy adopted very specific features, including a focus on mechanical engineering and the relative neglect of ICTs and value creation from platformization. Section 0 documented that this has raised criticism, also because of the risk of policy capture by vested interests. (Gault, 2010) argues that the risk of policy capture may be common in innovation policy design: a specific segment of advanced agents in the market take the lead in the development of certain technologies and applications that use those technologies; while this leadership may drive the development of the market, there is also a risk of biasing decision-making, while market dynamics gear towards serving the most advanced agents. The sophistication and leadership of the German mechanical engineering and automotive industries may prevent the development of the country's I4.0 strategy if not accompanied by broader cross-sectoral integration processes and to foster new business models in other areas.

Fourth, useful insights can be gleaned from Germany's experience so far:

- The development of the country's I4.0 strategy is open to accommodating policy experimentation and the fostering of intense public-private interactions. The mediating role of government consulting bodies (*Forschungsunion*, *Acatech* or EFI) facilitates dialogue, priority setting and knowledge exchanges.
- The establishment and operation of PI4.0 has made significant contributions to identifying and resolving coordination problems at sector level but has also fostered cooperation among stakeholders with divergent agendas.
- Standardization efforts are necessary to nurture suitable framework conditions for I4.0. The strategic use of standards can help develop and push through an ambitious agenda for economic transformation.
- Policymaking should build on strengths, systematically drawing from existing interventions with potential to contribute to I4.0. A high number of funding initiatives, some of which proved to be very successful (technological competitions and cluster strategies), helped attract the interest of different stakeholders. Both the BMBF and the BMWi operate with strong systems to document and evaluate their funded projects. The importance of developing and embedding sound monitoring and evaluation principles in the design of national I4.0 strategies cannot be overstated.

- Efforts to draw from international cooperation through PI4.0 has contributed to the development and setting of standards, to the setting up of testbeds, harmonizing skills and qualification programmes and cooperation in IT security. The effort to "learn from other industrial regions"[7] means that the bulk of bilateral and multilateral cooperation projects involve other developed countries, notably G20 members, where some form of a national I4.0 strategy is already in place.

[7] www.plattform-industrie40.de

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