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Is There a Smart Sustainability Transition in Manufacturing? Tracking Externalities in Machine Tools over Three Decades

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Abstract: Only one third of studies on the Industry 4.0–sustainability link have been conducted in manufacturing, despite its centrality to "ensuring sustainable consumption and production patterns" (UN Sustainable Development Goal nr. 12). The European Ecodesign Directive singled out machine tools as key to the sustainability transition, not least due to their high energy usage and their increasingly becoming enmeshed in cyber-physical production systems. This paper aims to find out whether the digital transformation underway in machine tools is sustainable as well as to identify its central technological pathways. Externalities in machine tools are tracked over three decades (1990–2018) by means of a multi-method setting: (1) mapping the Technological Innovation System (TIS) of machine tools; (2) co-occurrence analysis of transnational patent families, in order to reduce geographical and market distortions (Questel's FAMPAT); and (3) analysis of the incidence of digital and sustainable technologies in machine tools patent applications (WIPO PATENTSCOPE). A smart sustainability transition is currently not hampered by a lack of smart technologies but rather by the sluggish introduction of sustainable machine tools. Cyber-physical and robot machine tools have been found to be central pathways to a smart sustainability transition. Implications for harnessing externalities reach beyond the machine tools industry.

Keywords: digitalization; digitization; Industry 4.0; patent mapping; smart manufacturing; sustainable manufacturing; co-occurrence; Technological Innovation System; TIS

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1. Introduction

Most industrialized economies worldwide are currently undergoing a double structural shift. While the digital transformation is turning manufacturing operations into "smart" integrated networks, for which the term Industry 4.0 has been coined [1,2], a large-scale sustainability transition is unfolding in the form of "long-term, multi-dimensional, and fundamental transformation process[es] through which established socio-technical systems shift to more sustainable modes of production and consumption" [3] (p. 956), e.g., in the Circular Economy and Industry 5.0 [4,5]. Although Industry 4.0 started out as a policy-driven concept, recent studies have shown that it has begun to dominate scientific research agendas on a worldwide scale, particularly research on manufacturing [6–8], including machine tools [9].

The sustainable and digital transformations are playing out in quite distinct arenas. Although the very recent surge in scientific literature on Industry 4.0 testifies to a gradual process of amalgamation of Industry 4.0 with sustainability (e.g., [2,10–13]), their joint dynamics in a production and consumption context are still poorly understood [14]. Furthermore, there is a need for studies on the link between digitization (e.g., Industry 4.0) and sustainability to branch out into multiple disciplines [15], including economics. As smartness is equated with technologically efficient solutions, if these "perpetuate short-term, unsustainable ways of life then their claim to, smartness' is hardly appropriate" [16] (p. 695). By way of example, reconciling sustainability in production (e.g., through electromobility) with Industry 4.0 data tracking may prove to be difficult to accomplish: China has made real time monitoring of electric cars a prerequisite for production licenses which has led to additional data traffic amounting to 850,000 GB per year, an equivalent of over 4500 tons of yearly CO_2 emissions, which deduct from any emissions reductions achieved through electric mobility [17].

Only one third of studies on the link between Industry 4.0 and sustainability have been conducted in the manufacturing sector [18,19], which contrasts with the fact that manufacturing is considered indispensable for making a transition which is both smart and sustainable [20] in order to leverage the private sector's contribution to the UN Structural Development Goals (SDGs) [21], particularly that of "ensuring sustainable consumption and production patterns" (SDG 12) through the reduction of waste and better waste management [10].

Of all manufacturing sectors, machine tools have been identified as key to this sustainability transition due to their high energy usage, which has prompted their inclusion in an indicative list of product groups with significant improvement potential in the context of the European Ecodesign Directive [22]. Additionally, machine tools are increasingly becoming enmeshed in cyber-physical production systems [23]. A rather conservative industry with tight margins is thus put under transformative pressure [1] to make a double transition which is both smart and sustainable. Having played a strategic role in industrialization, especially in the United States [24], the state of the machine tools industry continues to serve as an indicator of the state of national innovation in industrial engineering [25] as well as of the state of global manufacturing at large, for which it is critical [26]. Rather than conducting a study of manufacturing in general, which would cloud sector differences, the machine tools industry was chosen for this paper due to its being a "bellwether of manufacturing acumen" [26] (p. 143) which indicates shifts in countries' competitiveness in manufacturing in a timely manner. As a cumulative systems technology comparable to semiconductors [27], machine tools are a linchpin for a sustainable transition of both production and consumption as they are enmeshed in intense user–producer interaction innate to the industry [28,29]. Consequently, the machine tools sector may offer a blueprint for the smart sustainability transition of economies at large. This will aid in better understanding the way in which digitization, innovation (as exemplified by the emergence of new technological trajectories and industries out of mature ones), and sustainability are intertwined.

This paper adds to the sparse literature on the link between the digital transformation and sustainability in the mature sector of manufacturing. It aims to determine whether the digital transformation underway in machine tools is sustainable, with the objective of identifying the central technological pathways of a smart sustainability transition. Based on a multi-method approach, the possibility of a smart sustainability transition being established empirically in the machine tools sector is investigated against the backdrop of the Technological Innovation System (TIS) approach in order to identify the technologies central to this transition. As the focus of machine tools industry studies has typically been regional [30] or national [31,32], this paper is the first to address machine tools as a global TIS with a focus on externalities. Externalities indicate a cross-fertilization of technological fields [33]. If inter-industry externalities materialize in smart and sustainable fields, these can be considered a marker of a smart sustainability transition which cuts across industry boundaries. The machine tools TIS is mapped in a timeline spanning the three decades between 1990 and 2020 in order to provide insight into the competitive field, including clusters as drivers of externalities. Externalities indicating new technological fields are then systematically tracked by means of a patent co-occurrence analysis (based on the patent database Questel's FAMPAT) for three decades beginning in 1990 (pruned to the year 2018 due to pending patent publications). Patent co-occurrences relate to IPC classes in which patents are jointly categorized during the examination process, and are considered a valid indicator of externalities as they are less prone to geographic distortions [34] and more reliably indicate knowledge flows in complex technologies as compared to patent citations [35]. The transnational ("world market") patents targeted in this study have scarcely been employed in patent analyses to date despite their effectiveness in greatly reducing geographical and market bias [36]. The latter is particularly important in a TIS such as machine tools with its decidedly global reach, visible in the growing world market power of China and South Korea. Furthermore, the incidence of digital and sustainable technologies in machine tools is measured by tracking and comparing PCT patent applications for the two periods, 1990–2004 and 2005–2018 using WIPO's PATENTSCOPE.

As it takes time for externalities to materialize, their existence can only meaningfully be ascertained in mature sectors [37], which have attracted less TIS research to date. This contrasts with the need to understand the crucial role of the maturity and decline of technologies in driving the sustainability transition [38]. In complementing the TIS framework by addressing externalities, the paper contributes to filling a long-standing research gap in TIS studies [33]. As opposed to a number of TIS models which either refrained from including externalities or inferred them from the existence of alliances and a shared labour pool rather than directly measuring them [39], this paper offers a direct measure of externalities based on patent data.

Contrary to expectations, a smart sustainability transition is currently not hampered by a lack of smart technologies but, at least to date, by the sluggish introduction of sustainable machine tools. Two Industry 4.0 trajectories have been established in the co-occurrence analysis: cyber-physical machine tools, which facilitate a prolonged life cycle of tools, and robot machine tools, which make use of modularity in order to decrease energy usage. By contrast, sustainable manufacturing in machine tools remains a niche phenomenon compared to Industry 4.0. The two Industry 4.0 trajectories identified with respect to machine tools may offer central pathways to a smart sustainability transition.

The paper is organized as follows. First, the results of a literature review are presented (Section 2), followed by the materials and methods employed in the study (Section 3). Then, the results of the TIS mapping and the two patent analyses are presented (Section 4). This is followed by a discussion of the results, including some limitations (Section 5). Section 6 concludes the paper and provides policy implications.

2. Literature Review

2.1. Interface of Digitization and Sustainability in Machine Tools

Existing literature reviews, however instrumental in charting the scientific terrain of sustainability and Industry 4.0 in its entirety (see e.g., [2,4]), are not sufficiently informative as to the specific research question of this paper, that is, the potential emergence of a smart and sustainable trajectory in manufacturing as exemplified by machine tools. Concrete applications in manufacturing, e.g., in smart factories [7,40], including smart machine tools, have not been investigated in-depth in their relationship with sustainability apart from case studies confined to particular types of machines [41]. Prior analyses of either the field of sustainability, Industry 4.0, or the link between the two [8] looked at the topic from a wide angle [40] and often included smart consumer products, which clouds sector differences. Studies on the link between Industry 4.0 and sustainability are plagued by the "double disease" [42] of a predominance of practitioner's reports on the one hand and a bias towards technological studies on the other. For instance, studies have dealt with recycling of, e.g., machine tool coolants [43] and industrial symbiosis [44,45], the digitization of machine tools [18] and sustainable, energy efficient machine tools [23,46] from a purely technological angle. Economic studies of the peculiarities of the smart sustainability transition in manufacturing are needed [11,42,47,48], and have a particularly crucial role as concerns smart machine tools [49].

Smart machines with sensors and actuators enable the tracking of thermal and mechanical deformation and offer automization potential in the production processes of machine tools [50]. Optimally matching machine tools and work pieces saves energy (e.g., in cutting and by reducing power losses) and thereby increases sustainability, which can be supported through adequate design of parts and tools [43]. Machine tools trained by means of deep learning help to minimize resource use and increase machining efficiency [9]. Facilitating knowledge and data exchange between materials, their digital twins and machine tools in cyber-physical production systems [51] further increases options for recycling and reuse, e.g., by means of electronic passports indicating the origin of materials employed in production, and allows resource savings from predictive maintenance. Producers can comprehensively track, monitor and mine production-related data over the life span of products and better align consumption patterns with resource availability as part of business models, including after-sales service, and, potentially relaunch products by means of remanufacturing [52]. Experience in the construction machinery industry demonstrates the successful remanufacturing of high-value components (generally the motor) and their subsequent reuse in a new product cycle [52]. This increases sustainability, as it saves on resources and prolongs the lifetime of machine tools and related machines.

The latest digital repercussion, flexible manufacturing cells based on microprocessors, may open up further sustainability potential through, e.g., improvements in the production technology of modular machine tools (as shown in life cycle assessments [53,54]). Modular machine tools have been produced in Japan since the 1960s in order to increase flexibility [55]. However, modularity is instrumental for sustainable machine tools as well, as it enables disassembly, recycling, and eventual reuse of end-of-life machine tools or their component parts, as modules are easier to disassemble than integrated parts [56]. This may become crucial in light of scarcities of necessary metals, and thereby contribute to higher levels of economic and ecological sustainability. The latest digitization wave of Industry 4.0 (Figure 1) could see machine tools become a set of fully-fledged general purpose technologies [57,58], giving rise to productivity gains in a wide range of sectors [28,59] comparable to nanotechnology [60].

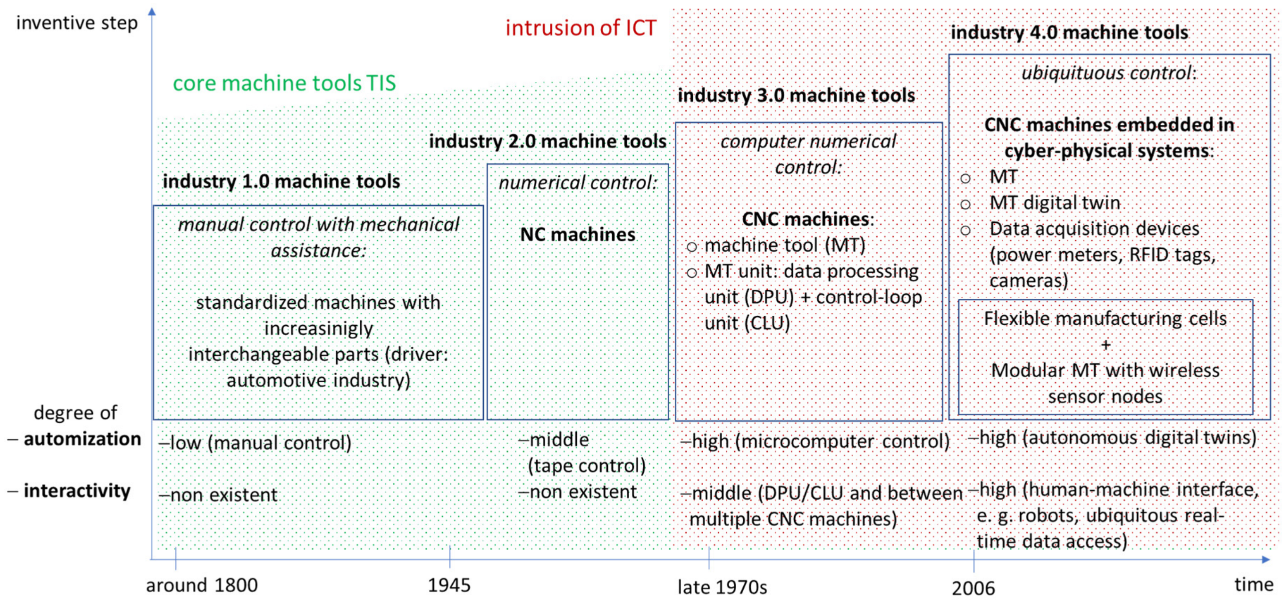


Figure 1. Evolution of machine tools from industry 1.0 to Industry 4.0. Source: own representation by author. For definitions and explanations on technological concepts mentioned see [23,53]; timeline indicates major watershed events without representing year spans in exact proportion.

In sustainable manufacturing, a decade of environmental studies has established increased resource productivity due to saved energy and materials use, e.g., in the moulding of car parts by means of additive manufacturing [61], which brings down production waste levels [7,62]. Although the Industry 4.0 technique of additive manufacturing is an emerging technology with a limited number of large-scale application cases to date [63,64], 3D printing may offer a case in point of a smart and sustainable technology. For instance, in the production of medical technology the use of strategic metals like tungsten has been considerably reduced by employing 3D printing, increasing both economic and ecological sustainability. Based on data on science funding and publications in machine tools, the future of the machine tool industry has been projected "to be low energy, high efficiency, green and sustainable" [9] (p. 16). However, additive manufacturing technologies such as selective laser melting require an elaborate preparation of feedstock materials and post-processing, which decreases material efficiency [65] and could exacerbate resource consumption and compromise sustainability [63]. Remanufacturing of outdated milling machinery leads to the employment of machines which may be put to efficient use only with materials processed at low-cutting speeds, such as nickel-based alloys, and which are not able to be used with materials such as aluminium alloys which require a higher cutting speed [66]; the result is less energy-efficient machine tools.

Evidence of the sustainability impact of Industry 4.0 machine tools is thus all but equivocal [11], as functionality and cost considerations have dominated machine tool design so far. Green manufacturing initiatives (beginning in the 1990s and targeted at a broad spectrum of industries) have sought to minimize energy consumption of machining systems and machine tools over their lifespan [46,67] and, more recently, investigated their potential to scale down resource consumption and environmental discharges more generally by including all material resource costs (e.g., scrap iron, externalities of coolants) incurred by manufacturing [43,58]. Though machine tool choice figures as a decision parameter in these models, the machine tools sector is reduced to a supplier of a productive resource and user of non-renewable energy sources from an engineering point of view, and does not figure as an economic unit of analysis of its own. By contrast, the machine tools innovation system is investigated here against the backdrop of the TIS approach, with a particular focus on whether the machine tools trajectory is permeated by a smart sustainability trajectory.

The focus in this paper lies on the interface between the economic and the ecological sustainability pillars in manufacturing [63], with the economic pillar [7] less solidly founded than the ecological [21]. While examples such as smart machine tools [50] which are sustainable through being more energy-efficient than traditional tools [23,46] do exist, the question remains whether these are singular events or if they are piece and parcel of a wider-reaching smart sustainability transition in which digital and sustainable technologies reinforce each other. With the risk–return profile of Industry 4.0 largely unknown and its repercussions spanning all areas of the triple bottom line [6], more theoretically-grounded research is needed on the intersection between Industry 4.0 and sustainability on the level of mature sectors, particularly in machine tools.

2.2. TIS Research on Externalities

Two types of externalities, intra-industry (Marshall type) and inter-industry (Jacobs type) externalities have been identified in the literature on economic geography [68] based on the seminal works of Marshall [69] and Jacobs [70]. In TIS research, externalities have been found to originate from "problem-solving networks in the form of user-supplier links" [71] (p. 201) and, in the tradition of Marshall, have been inferred from the existence of three factors: specialized suppliers, a pooled labour market, and knowledge spillovers [72]. Spillovers have been shown to be central to an economy's ability to transform research and development results into long-run growth [73]. This perspective is compatible with clusters specializing in a particular technology, that is, intra-industry spillovers. By contrast, diversification into fields which are mostly similar to the current core field while offering novel ideas in the sense of related variety [74] (inter-industry spillovers) have been considered essential for the development of a TIS [75].

TIS researchers have expressed the need to expand the range of empirical cases by addressing sectors outside the energy sector, and particularly to address multi-sector interaction [76] in mature sectors [38], which can give rise to inter-industry externalities [75,77]. Inter-industry externalities indicate a cross-fertilization of technological fields [33] and contribute to a revamping of functional patterns of production and consumption [78] across industries, particularly in TIS located upstream in the value chain [79], such as machine tools. Inter-industry externalities are thus a key process driving Technological Innovation System, not least through an acceleration of the diversity of actors in a TIS [72], which increases the likelihood of an advantageous adoption of bottom-up policies (e.g., green manufacturing) backed up by broad advocacy coalitions [80]. Tapping into the resources of heterogeneous partners to form these beneficial coalitions is crucial in the digital transformation [15]. Due this multi-industry embeddedness [58], the machine tools TIS brings together the requisite heterogeneity of actors indispensable for a shaping of the corresponding layers of the selection environment [81] in this mature but highly innovative and dynamic [82] TIS.

This paper focuses on these essential inter-industry externalities which induce innovation, whereas intra-industry externalities are more likely to lead to imitation [83]. Examples of inter-industry externalities include combinations of machine tools with ICT and climate change mitigation technologies, which leads to new production ecosystems (e.g., smart factories with sustainable, energy-efficient machine tools) or services (e.g., Industry 4.0 Servitization combined with Repair and Reuse). Apps which enable exchange and reuse of knowledge between autonomous tools are a symptom of a more general reconfiguration of the machine tools value chain with "cross-border competition", particularly between ICT firms, electronics firms and traditional machine tools companies becoming "the norm in the future" [9] (p. 20). The long lifespan of machines necessitates regular maintenance, and gives rise to intense user-producer interactions over a product life span, which will be additionally spurred by digitization [84].

The mature sector of machine tools has thus far been mainly conceptualized as a regional [30,84] or national innovation system [25,31,32] or studied on the firm level [84,85]. Based on multiple data sources (as in the present paper), Chen et al. [9] provide an analysis of the evolution of the machine tool sector from the viewpoint of funding and topical networks, although without embedding it in a theoretical framework, as is done here against the backdrop of the TIS approach, and without exploring externalities. An early contribution to the exploration of machine tools as a TIS avant-la-lettre was provided by Rosenberg [24] and re-evaluated for differences and communalities with the ICT sector by Bresnahan in 2019 [29]. While the latter study [29] focuses on the ICT trajectory in isolation (e.g., exemplified by software as service, big data, and Artificial intelligence), this paper is interested in the convergence patterns of ICT with sustainable technologies in machine tools.

3. Materials and Methods

In answer to the plea made in the tech-mining approach, which mandates a combination of analysis of scientific literature with patent analysis in order to trace technological trends in an informative, reproducible, and efficient manner [86], this paper investigates the evolution of the machine tools TIS over the last thirty years by employing a multi-method design. Based on a broad literature base, a TIS mapping analysis was first conducted, followed by two in-depth patent analyses covering the same time frame.

The TIS map was based on a literature survey (scientific literature, industry reports) and on patent data, with the timeline spanning a series of events from the first appearance of the term 'sustainability' in an ecological-economic-social context in 1987, to the inception of cyber-physical production systems in 2006 [1], to Industry 4.0 in 2011 [87], to the Circular Economy Action Plan and Industry 5.0 of the European Commission in 2015 and 2019, respectively.

The patent co-occurrence analysis was based on a proprietary patent database (FAMPAT of Questel's Orbit Intelligence database) and an open access patent database (WIPO PATENTSCOPE) in order to ease replication, as encouraged by Börner and Polley [88]. Patents can be considered as a proxy for technological development [89] and have been used as a means to identify the developmental stage of a TIS [90] along with technological sub-trajectories and trends [91] mirrored in patent maps and patent networks.

With the aim of mapping the technological trajectories of the machine tools TIS as closely as possible from a technological rather than national angle, it was important to avoid a geographically distorted picture of patenting in machine tools. In keeping with the global reach of the machine tools TIS following its dominant customer, the automobile industry, a national system demarcation targeted at machine tools patents taken at only one patent office was therefore inadequate, as such a patent sample would only reflect part of the relevant world market. While the Worldwide Patent Statistical Database of EPO (PatStat) contains patent data from countries in different technological developmental stages, USPTO patents are more informative as to the longitudinal patterns of cutting-edge technology [92]. However, the distortion of patent counts due to strategic patenting is more prevalent in the USPTO than in other databases [93]. In order to reduce geographical bias, triadic or transnational patent families may be considered instead. Many studies to date have employed triadic patent families which have been applied for at each of the three patent authorities (USPTO, JPO and EPO) and share at least one common priority [94]. An alternative to triadic patents are transnational ("world market") patents, which are patents filed over the international PCT route irrespective of their subsequent application at the EPO, plus all those patents filed directly at the EPO without prior PCT application [36] (the latter is important in order to avoid double counting); this has been shown by the same authors to greatly reduce geographical and market bias.

Transnational patents were preferred over triadic patents in this paper for two reasons: as the USPTO published only granted patents until the year 2000 and not applications, the first ten years of the sample period would see patent grants (USPTO) and applications (JP, EPO) mixed, with further delays due to patent pendency [36,95]. Second, and more importantly, international trade flows, particularly of newly industrialized countries, are incompletely captured by triadic patents [36]. In light of the growing world market power of China and, more recently, South Korea in machine tools, this would be a serious omission; therefore, transnational patents are the basis of the following co-occurrence analysis.

Patent co-occurrences were employed as a measure of externalities. Patent co-occurrences have previously served as an estimate of the technological significance of patents and as a way to map transitions in technological landscapes over time [96,97], and can offer a valid way to measure externalities [89,98]. Patents are usually filed in more than one IPC class by expert examiners [99], and the fact that two or more IPC classes occur together in the same patent (co-occurrence) can be used as an indicator of externalities flowing between the respective technological fields covered by these classes. The allocation of IPC codes to patents is an indicator of the developmental state of a technology, and it has been argued that additional text mining on patent documents is dispensable as the analysis can be directly focused on the IPC codes or subclasses thereof [95]. The 4-digit level of IPC classes (level of subclasses) was chosen in this paper, as this is most appropriate for analyses pertaining to the level of technologies rather than to specific countries [100]. In this way, the set of technologies covered is large and detailed enough to allow increasing or declining technological fields to be uncovered with a good degree of accuracy [95]. The methodology of measuring co-occurrences builds on prior work by the OECD [98] which has been used to analyze technology emergence in nanobiotechnology [101]; in the context of this paper, it was applied with the aim of uncovering a smart sustainability transition in a mature sector.

Citation analysis was not utilized as an alternative way of measuring externalities in this study. The fact that a patent has been cited by another patent can be considered a measure of knowledge flowing between the two patents, and citations have thus been employed as a means to identify clusters between topical fields and the proximity relations of firms' patent portfolios [92,102]. However, as the majority of patent citations are made by patent examiners [103], citation as a measure of externalities offers the same level of objectivity as co-occurrence, with the added disadvantage that inventors are often unaware of cited patents when launching their invention [104]. Furthermore, patent citations have been shown to be geographically distorted [34] and subject to strategic patenting, in addition to being a less reliable indicator of knowledge flows in complex technologies [35]. The latter compromises the usefulness of patent citations as a measure of externalities in machine tools, as these are increasingly complex general purpose technologies. A co-occurrence analysis based on transnational patents (Questel's FAMPAT) and an analysis of the incidence of digital and sustainable technologies in machine tools based on PCT patents (WIPO PATENTSCOPE) were therefore conducted in this paper. As a starting point, the TIS mapping analysis set the stage for the ensuing focus on the function of the development of externalities provided by the two patent analyses.

4. Results

4.1. TIS Mapping Analysis

Centering around a focal technology [33,105], the TIS framework links functions (among them the development of externalities) as key innovation-related processes of the system [80] to its components (like producers and consumers) which in a more or less concerted fashion contribute to overall system performance [77,106]. TIS studies usually refer to a set of seven system functions [72,77,80,107,108]. The system functions highlighted in bold face type in Figure 2 are in concurrence with those employed in existing studies but, in contrast to these studies except for [80], include externalities. The paper goes beyond [80] by including negative externalities as well. The most important basic TIS functions with respect to the shaping of the technological expansion path, namely, guidance of the search, knowledge development and diffusion, and the hitherto-neglected function of positive externalities [72,80] will be particularly focused on in the following; the term 'externalities' is used here instead of 'positive externalities', in order to include potential negative spillovers, e.g., those induced by market-stealing [109] in intra-industry and, increasingly, inter-industry competition.

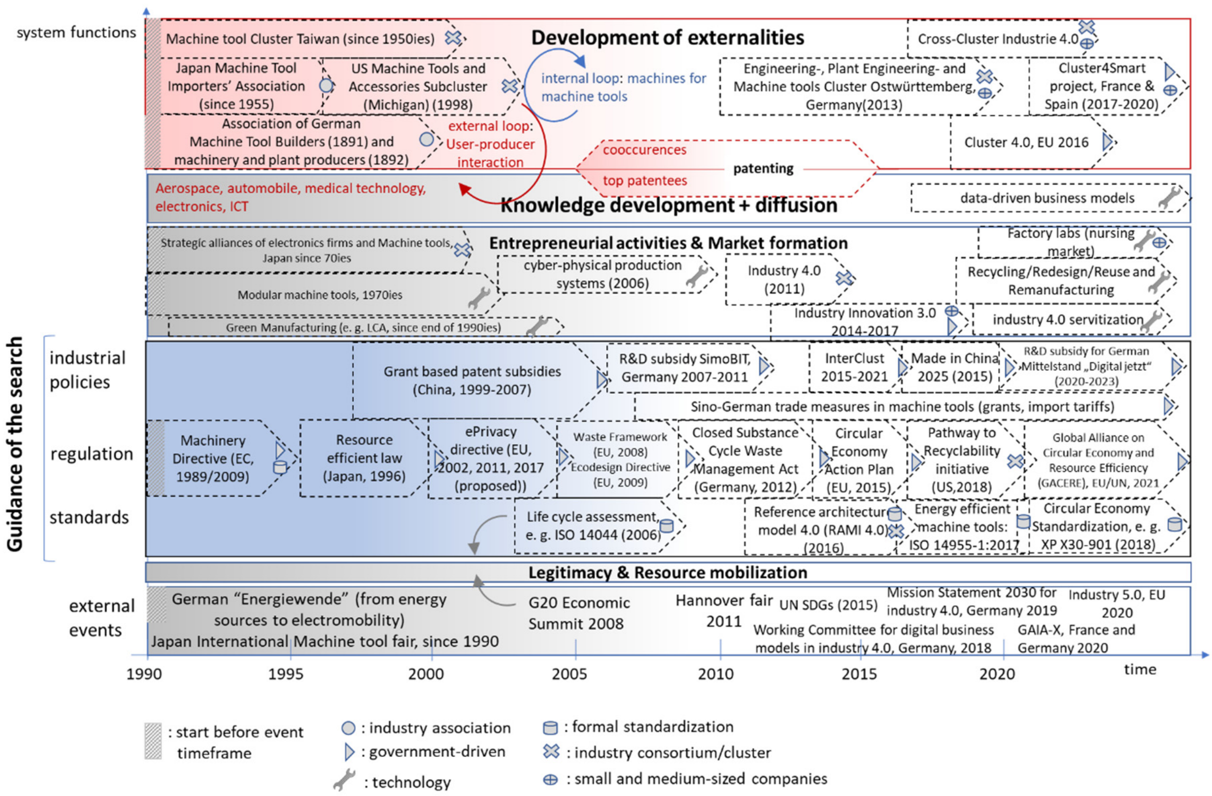


Figure 2. Mapping of the machine tools TIS. Source: own representation and data compilation by author. The legend is similar to [81]. For laws and directives, the first year of drafting and year(s) of subsequent update and coming into force are given. Source of tool icon: https://pixabay.com/vectors/tool-wrench-screw-wrench-161323/ (accessed on 1 December 2021).

The TIS map (Figure 2) cannot claim to provide a comprehensive picture of the machine tools industry in its global reach, though every effort was made to map the main activities of the competitive fields, including the most important global players in the TIS (proxied by top patentees) as mirrored in industrial policies, standardization, and industry cluster initiatives, among others, and to tentatively outline functional pathways.

4.1.1. Knowledge Development and Diffusion

The development of externalities is inextricably intertwined with knowledge development and diffusion in machine tools. Knowledge is created through a double loop: an internal loop, as machine tools firms produce the machines with which machine tools are produced in turn, and an external loop, as their "infinitely modifiable product[s]" [110] (p. 163) afford constant user–producer interaction. This can give rise to externalities based on complementary types of knowledge from suppliers and users [78,80]. Knowledge development is fuelled by this inherently "social process of machinery design and production" which is indispensable for leading-edge customized machinery [31] (p. 95) and propels innovation in various downstream industries which employ machines "descending" from machine tools as their mother machines [41,111].

This knowledge is then at least in part channelled into codified forms, e.g., taking the shape of patent trajectories. Overall, Japanese applicants have launched the most machine tools innovations as measured by the number of granted patents between 1990 and 2018, followed by China, the USA, and Germany (Table 1 and Figure 3). The countries of origin indicate where the inventive work was carried out, rather than where the patent has been filed.

Table 1. Top four patenting countries in which machine tool patents (technology class nr. 26) have been granted worldwide 1990–2018.

Applicant Country of Origin	Total Number of Machine Tools Patents (Granted 1990–2018)
Japan	174.898
China	100.861
USA	97.416
Germany	77.662

Equivalent count, top patentees only, fractional count of patents which have been assigned multiple IPC codes and therefore belong to several technology classes in the period 1990–2018. Source: based on data retrieved from WIPO Statistics Database of World Intellectual Property Organization which draws on PatStat, last accessed on 27 October 2020 .

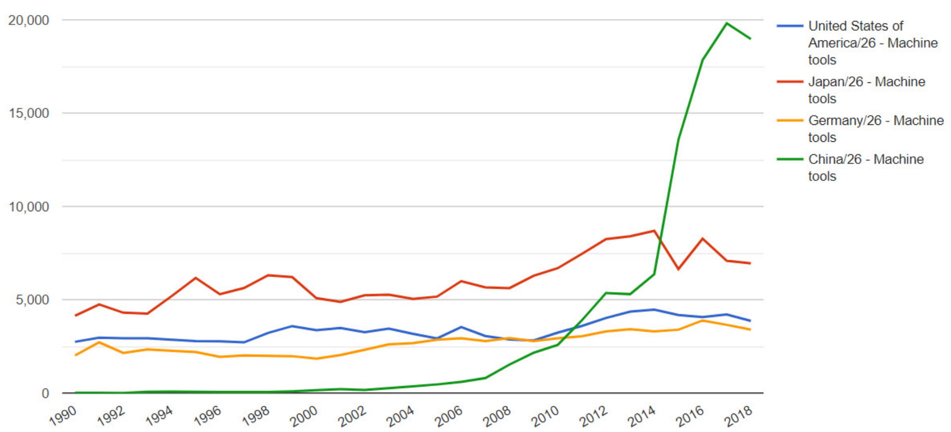


Figure 3. Total count of patents granted worldwide in machine tools (technology class nr. 26) by country of origin. Equivalent count, top patentees only, fractional count of patents which have been assigned multiple IPC codes and therefore belong to several technology classes) in the period 1990–2018. Source: own representation by author based on data retrieved from WIPO Statistics Database of World Intellectual Property Organization which draws on PatStat, last accessed on 27 October 2020.

Notable is the recent surge in the number of granted Chinese patents (green line in Figure 3), although the quality of these may be lower compared to peer economies [112]. China has gained substantially in both employment and in the share of its manufacturing value added in global GDP between 1994 and 2014 [113]. However, technological capacity, when correcting for patent quality, is considerably lower in China than total patent numbers would suggest [112]. In fact, 30% of the surge in Chinese patenting has been traced back to the policy of grant-based patent subsidies initiated between 1999 and 2007, resulting in lower-quality patents with narrow claims [114].

The five leading companies in terms of patent applications over the studied time span are Robert Bosch GmbH (Stuttgart, Germany), Illinois Tool Works Inc. (Glenview, IL, USA), Siemens Aktiengesellschaft (Berlin/Munich, Germany), 3M Innovative Properties Company (Saint Paul, MN, USA), and JFE Steel Corporation (Chiyoda, Japan), as an analysis by the author based on [115] has shown. While Robert Bosch GmbH had far more patent applications, with 1945 compared to the second-ranked Illinois Tool Works (897), it owes this position primarily to patenting in the first two decades of the thirty-year time span under review, maintaining its top position only until 2013 when the US company Illinois Tool Works applied for most of the patents in the field for the first time. A first indication of the importance of inter-industry externalities is provided by the third-ranked company, Siemens, being a company with a non-machine tools background positioned centrally among patentees, in this case a conglomerate with a focus on digital industry solutions, Internet of Things, and additive manufacturing. It is followed by another company from outside machine tools, 3M, which specializes in electronics materials. This underlines that the shift towards a smart transition in machine tools is corroborated by a growth in patenting activity from outside machine tools and by rising levels of cooperation between electronics firms, ICT companies, and machine tools companies. By way of example, electronics firms such as Matsushita and General Electric have entered into co-operative ventures with classical machine tools companies such as Fanuc in the last decade, which on their own part have launched a growing share of electronics and artificial intelligence patents and co-operative ventures with, among others, the artificial intelligence startup Preferred Network from Japan [9].

4.1.2. Guidance of the Search

A firm's principal products guide both the direction and rate of search, while unexplained variance points to a certain leeway in the search for new technological trajectories [116]. In transferring this to machine tools, companies in the field are constrained by the accumulated technological competences pertaining to their core product(s), and may push open windows of opportunity to attain new ones. The latter process is guided by standards which curb and channel expectations of producers and users towards a universally-acknowledged technological state of the art [59], giving rise to new expansion paths [117]. Both Industry 4.0 and sustainability standardization have intensified worldwide since the turn to the 21st century. CNC machine tools, as high-tech systems technologies (consisting of controllers, sensors, etc.), require interface standards which enable, for instance, both modularization and sustainable design, provided that premature standardization implemented too early in the product life cycle is avoided, as this compromises the evolution of superior performing product platforms [117]. Standards thus both mimic and boost the further evolution of the TIS, and can have a nurturing and a blocking influence on the TIS depending on their timeliness and breadth. For Germany, nurturing through standardization has been facilitated by the platform RAMI 4.0 beginning in 2016, a reference architecture for Industry 4.0 production settings which reinforces legitimacy-driven adaptation, as the technology's reliability is perceived to be high [77].

Conformative pressures within the function Guidance of the Search arise from Circular Economy regulations such as the Pathway to Recyclability Initiative in the US (2021) and the Realisation of Acceleration of a Circular Economy (RACE) program in the Netherlands (2014) on a national level, and the Waste Framework and Ecodesign Directives of 2008 and 2009 on a transnational level. German producers of machine tools now face more severe recycling regulations (e.g., through the extended manufacturers' liability in § 23 of the Closed Substance Cycle Waste Management Act 2012), necessitating prolonged use phases of their products and design for recycling and reuse. On an EU level, the Machinery Directive, last updated in 2006, was originally addressed to machinery manufacturers and consumer protection agencies as a means to increase social and ecological sustainability by protecting health, safety, and the environment [118]. However, lobbying activities by the European Association of the Machine Tool Industries and related Manufacturing Technologies reveal that they expect artificial intelligence, cybersecurity, and digital documentation to be part of major revisions of the Directive in the course of 2021, which they wish to be gradual rather than radical [119]. A similar stance was taken towards the European ePrivacy Directive, which companies and industry associations feared would hamper even machine-to-machine data exchange and slow down the Industry 4.0 transition [120].

The function Guidance of the Search is driven by industrial policies which are undergirded by external events, e.g., the prominent positioning of Industry 4.0 at the Hannover Fair in 2011 which, in Germany and beyond, triggered a series of government-subsidized programs targeted at Industry 4.0 and digitization which peaked in the Mission statement 2030 for Industry 4.0 in 2019 and the launch of the GAIA-X platform, a joint digital platform initiated by the German and French Ministries of Economics, in 2020. Similar industrial policies and entrepreneurial activities have been launched in Korea (Industry Innovation 3.0) and China (Made in China 2025) with a focus on machinery, automotive and artificial intelligence (China), and automotive and ship building (Korea). In Korea, based on a USD 200 million industry budget, counselling has been offered by large companies to small- and medium-sized second- and third-tier vendors since 2014 with the aim of accelerating the Industry 4.0 transition [121]. On the sustainability side of the equation, the energy transition, e.g., the German "Energiewende" starting in the early 1990s, has gained momentum with the phasing out of nuclear power in 2011 and the European Green deal by the end of 2019, both of which have increased pressure on the manufacturing industry in general and machine tools in particular to adopt a sustainable technological paradigm, e.g., through more energy efficient machine tools. In Germany, a central part in industrial policy has been played by the funding scheme Internationalisation of Leading-edge Clusters, Future Concepts and Networks (InterClust) created in 2015, through which EUR 100 million will have been invested by the German Federal Ministry of Education and Research by the end of 2021. A positive evaluation highlights this two-track strategy of combining a traditional place-based policy with a rigorous internationalization scheme inducing externalities beyond the regional level [122].

Industrial policy measures have given rise to negative externalities as well, e.g., through trade distortions in the capital goods industries. As opposed to the US, the Japanese and German machine tool TISs have been more deeply embedded with the institutional infrastructure supplied by their national innovation systems, e.g., in the form of research and development subsidies, human capital, and export promotion, with decidedly more interventionist policies in Asia [110]. Between 2008 and 2020, China has been responsible for the largest share of trade restrictive measures targeted at the machine tools sector and related product classes worldwide (16.5%), followed by Brazil (5.3%), India (5.0%), and Argentina (3.0%), with the data being current as of 5th July 2021. Chinese interventions have come most often in the form of financial grants to the domestic machine tools industries along with import tariffs, which mainly affected the United States, Germany, and Japan [123].

4.1.3. Externalities

Externalities have been defined within the TIS framework as complementary interactions of rival technologies or industries [80], e.g., between machine tools and an array of related sectors such as die firms and customers from the durable goods sectors [26]. The inter-industry, Jacob-type externalities which are at the centre of this study result from an overlap between competing but complementary technologies, and are the result of the intrusion of more remote technological categories into the core trajectory [124] of a TIS [80,90]. Inter-industry externalities create novel combinations of existing technologies or entirely new technologies in sectoral niches [75], and result in “system-level utilities” being created “which are available also to system actors that did not contribute to building them up” [37] (p. 23). Business models driving the search for feasible solutions within the TIS [80], e.g., Industry 4.0 servitization, tool wear prediction [53], and other data-driven business models have emanated from the ICT sector and spilled over to machine tools since the early 2000s as an example of materialized positive externalities. While intensified user–producer interaction through Industry 4.0 is expected to contribute to the industry’s innovation capacity, the transition will come at the cost of decreased investment in tangible production systems (the established business model of machine tool builders), and machine engineering companies voice concerns about the market entrance of ICT companies exacerbating competitive pressures [11], with the latter pointing to negative externalities.

Externalities have also emanated from strategic alliances and clusters. Strategic alliances between electronics firms such as Fujitsu and machine tools companies such as Toyota Machine Works have been the most prevalent innovation mode since the 1970s in the once-dominant Japanese machine tools sector [55]. Clusters are an indicator of institutionalized externalities, e.g., the German engineering, plant engineering, and Machine tools cluster Ostwürttemberg founded in 2013, in which 160 small- and medium-sized companies engage in complementary inter-industry knowledge development and diffusion. User–producer interaction and clusters may see a renaissance, as these examples mirror the traditional need for close proximate ties with high end customers innate to the industry without the former obstacles to the transmission of technological data [31], as interaction may be facilitated effectively in blockchain infrastructures with real-time tracking of data [125]. This will make proximity in clusters less important. For instance, in the machine tools cluster of Taiwan, located in the agglomeration around Taichung City, companies such as Hiwin Technology produce high-end Industry 4.0 machine tools. Cross-border pipelines between Taiwan and China have created off-shore industrial systems with production located in both countries [30], intensifying the global reach of the machine tools TIS. By contrast, the Japanese innovation system finds itself increasingly insulated due to a lack of co-inventor networks in patenting compared to Germany and Denmark, with low connectivity of Japanese firms, particularly in electronics and robotics [126], which are instrumental to a digital transformation of machine tools.

User–producer interaction and inter-industry clusters have been used in TIS research as rough indicators of externalities, although generally serving to indirectly infer rather than directly measure externalities. Therefore, the ensuing patent analysis will help to further flesh out the role of externalities in the functional grid of the machine tools TIS. After first retrieving the top patentees in machine tools by country of origin (inventor perspective) in this section (Figure 3), the opposite focus, on target countries (market opportunity perspective), is taken in the subsequent co-occurrence analysis. These analyses aim to provide a more reliable measure of externalities than the mere existence of clusters and alliances can afford.

4.2. Co-Occurrence Analysis Based on Transnational Patent Families

In line with the results of Frietsch and Schmoch [36] in the context of telecommunications, this study established a higher patent family count of transnational machine tools patents than of triadic patents, both retrieved from FAMPAT, for the time span 1990–2018 (Figure 4), mirroring the less-distorted representation of newly industrialized economies such as South Korea, China and India in the transnational sample.

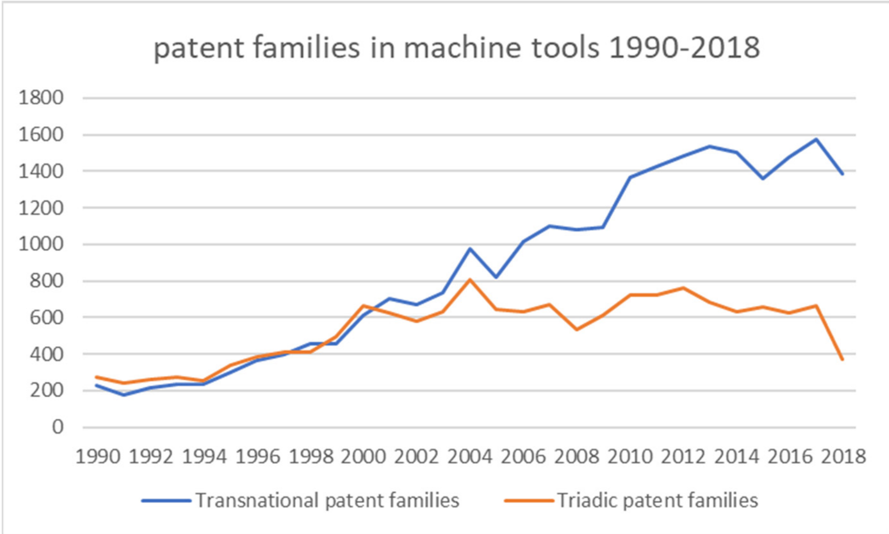


Figure 4. Development of patent families in machine tools by first application year (25.003 transnational and 15.593 triadic patent families in time span 1990–2018). Source: own representation by author based on patent families retrieved from Questel's FAMPAT, accessed on 28 February 2021.

Counting families, i.e., patents belonging to the same priority application with only one family member counted, yields distinct inventions [101]. The time span is the same as in the TIS map, except that the last two years have been omitted, as patent applications require up to 18 months to be published, and patents applied for in 2018 or later would thus not be fully reflected in the data.

The results of a detailed classification-based patent family search targeted at IPC co-occurrences for the time span 1990–2018 are presented below. The patent search was conducted on 21st and 28th February 2021 based on FAMPAT (Questel's Orbit Intelligence database), a patent database which covers patent applications by over 100 patent authorities and incorporates a unique "strict and enriched" family construct which yields distinct inventions and reduces black sheep [127] in patent families. Strict and enriched means that members have the same priority number (strict) and that different procedures of national patent offices are taken account of (enriched) while correcting for reporting errors (reducing black sheep) [128]. The classification search strategy included the core class of machine tools (B23) enlarged by further classes in line with the technology–IPC classes–concordance table of Schmoch [129], with the class B25J added in order to be able to cover newly emerged Industry 4.0 technologies within machine tools. Some 70% of German machine tools are shaping tools, particularly metal-cutting machines [130] belonging to IPC class B23, as opposed to pressing, e.g., forming or stamping machines. Metal-cutting machines have the highest energy consumption [131], which increases their relevance in the context of sustainability. Therefore, the most relevant technologies in machine tools from the perspective of this study are covered (for full search string see Appendix A).

Co-occurrences of IPC codes as a measure of inter-industry externalities [95,98,132] indicate new technological fields arising at the interface of existing industries, e.g., between the core class B23 (machine tools belonging to the technological field of Performing Operations and Transporting) on the one hand, and more technologically remote classes from other disciplines such as G05B (Physics) and H05K (Electronics) on the other.

The following figure shows the 100 most often co-occurring pairs of IPC subclasses in transnational machine tool patent family applications with their earliest priority dates within the two timespans, 1990–2004 (blue bubbles) and 2005–2018 (orange bubbles), respectively (Figure 5). Larger bubble sizes indicate a higher number of patent families in which the respective subclasses co-occur. Externalities occurring in both periods are displayed above the diagonal, whereas externalities occurring in only one of the two periods are displayed below the diagonal.

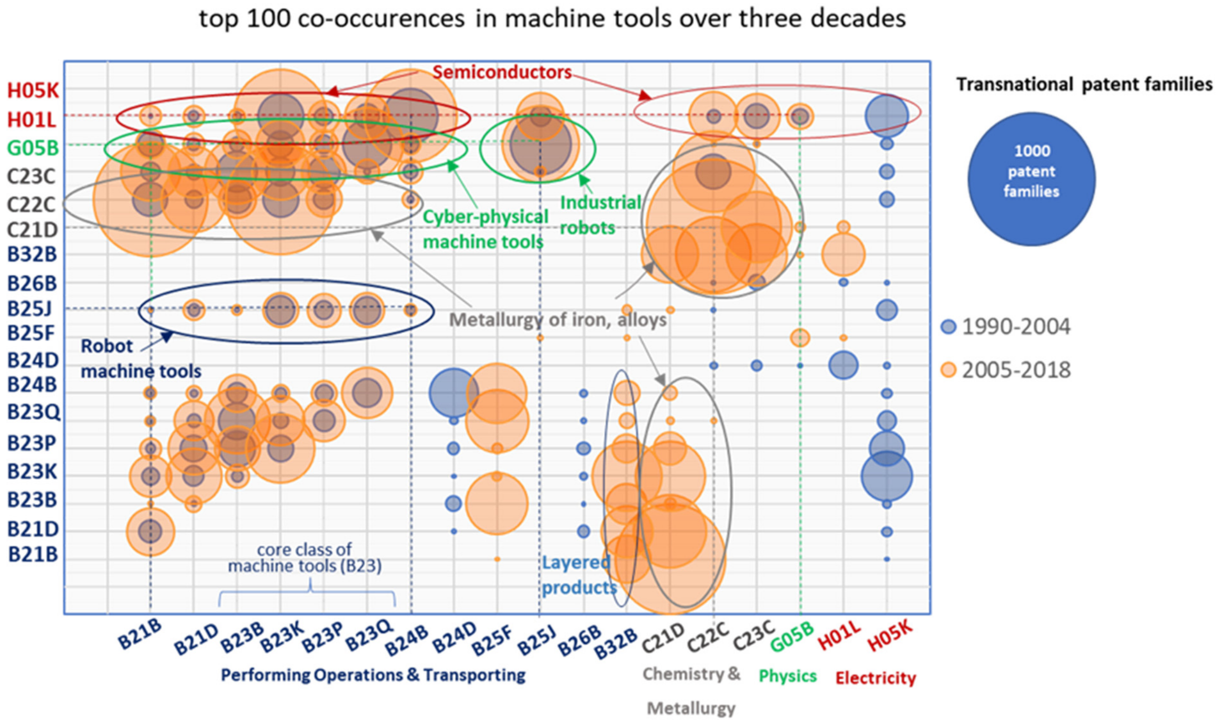


Figure 5. Top 100 co-occurrences of IPC subclasses in machine tools. Co-occurrences based on 3.225 patent families in the period 1990–2004 and 15.511 in the period 2005–2018 (after removing duplicates). Co-occurrences appearing in one period only are displayed below the diagonal (see Appendix A for the search string and Appendix B for a concordance table of technological fields and the IPC subclass codes in this figure). The blue bubble in the legend provides an indication of the number of patent families associated with bubble size. Source: own representation by author based on data retrieved from Questel's FAMPAT, accessed on 21 February 2021.

All externalities already present in the first timespan have increased in the more recent time period, as indicated by orange bubbles with a smaller blue core throughout. The number of patent families has more than quadrupled in the more recent time period, that is, in the past thirteen years. Three fields where inter-industry externalities now span larger parts of the IPC codes in the sample, and are thus likely to induce innovation rather than imitation [83], are semiconductors (combinations of H01L with machine tools, indicated by the red oval in Figure 5), cyber-physical machine tools based on smart monitoring and control systems (combinations of G05B with machine tools, indicated by the green oval), and metallurgy of iron and alloys (combinations of C21D and C22C with machine tools, respectively, indicated by the grey ovals).

Among the co-occurrences that have disappeared in the more recent period are all combinations of H05K (printed circuits) with B23, the core class of machine tools, as indicated by purely blue bubbles on the right rim of Figure 5. Newly emerged in the second time span are categories from metallurgy, indicated by purely orange bubbles with grey ovals in the lower right half of Figure 5.

Semiconductors (H01L), microchips consisting of integrated circuits printed on silicon wafers [133], have gained traction in almost all technological fields. Semiconductors are indispensable for all types of embedded electronics in machine tools, and by way of miniaturization, even more so for modular machine tools with wireless sensor nodes in emerging cyber-physical production systems. The prevalence of semiconductors combined with machine tools in both periods (red oval) can be interpreted as a sign of an amalgamation of machine tools with Industry 4.0 technology; however, this reaches back farther into the beginning of the era of computerized CNC machine tools as well (see Figure 1).

Industry 4.0-related externalities have entered the machine tools TIS along one of two trajectories:

Trajectory 1: First, Industry 4.0 technologies have become intertwined with machine tools by making them part of cyber-physical production systems resulting from co-occurrences between monitoring and control Systems from Physics (G05B) and the wider machine tools categories (B21–B24, including the core class B23), turning the latter into cyber-physical machine tools, as indicated by a green oval in Figure 5. Monitoring and control systems (G05B), comprises Industry 4.0-related subclasses related to computer-controlled systems and simulators (G05B15/00 and G05B17/00) embedded in machine tools by means of digital processors (G05B19/042).

Externalities furthermore exist between the two Industry 4.0 categories themselves (G05B × B25J); B25J refers to Manipulators covering "handling tools, devices, or machines [. . .] being controlled by means remote from the head, e.g., programme-controlled industrial robots" [134]. Externalities between these categories (G05B × B25J) result in industrial robots, visualized by the smaller green oval, and have been the top co-occurrence in the first timespan (254 patent families). Although their incidence increases again in the second timespan (407 patent families), these are trumped by the aforementioned cyber-physical machine tools, amounting to 639 patent families in the second time span and marked by the larger green oval in Figure 5.

Trajectory 2: Second, smart technologies have entered the machine tools TIS as a result of co-occurrences between manipulators, e.g., tools controlled by robots (B25J), and the wider machine tools categories (B21–B24), turning the latter into robot machine tools, as indicated by the blue oval in Figure 5. While the incidence of these robot machine tools is still small in terms of absolute numbers compared to trajectory 1, it has been increasing steeply (by nearly 50 %), from 130 patent families in the first period to 250 patent families in the second time span. This is compatible with the observation that new trajectories lag behind established trajectories with regard to the existing technological frontier (here, the core machine tools category, B23), which requires problem-solving to start almost entirely from scratch in the new trajectory [124].

These results suggest that machine tools are becoming embedded in cyber-physical production systems as the dominant mode of Industry 4.0 implementation in machine tools to date (trajectory 1), followed by directly turning machine tools into robot machine tools (trajectory 2).

Examples of recent patent publications (published in 2020 and 2021) in these two trajectories are given in Table 2.

As to the sustainability impact of these smart types of machine tool, by way of example, the texts of the patents for a cyber-physical machine tool (Table 2, Trajectory 1, WO/2020/136899) and for a robot machine tool (Table 2, Trajectory 2, EP3854536A1) are analyzed here in greater detail. The cyber-physical machine tool allows for controlling the vibration of a cutting tool and prevents chips from becoming entangled with the tool, which increases its overall lifetime [135]. The robot machine tool patent covers a multifunctional tool which can be "used as an end-effector on a robotic arm" [136]. Tooltips allowing for cutting, grasping, drilling, etc., can be replaced and do not require separate motors, which results in machines of less weight and "reduces overall system power requirements, and system complexity" [136]. This second example demonstrates how modularity as a basis for making tools interchangeable can positively impact sustainability by means of lower weight and less energy consumption.

The sustainable technology of additive manufacturing, which induces resource savings in the production and employment of machine tools (B22F and B33Y), was not among the top 100 co-occurrences, and accounted for less than 2% and 1% of transnational patent families, respectively, over the whole sample period.

Table 2. Examples of patent applications in the two Industry 4.0 trajectories from the co-occurrence analysis.

Trajectory		IPC Class Co-Occurrence	IPC Classes of Example Patent	International Publication Number of Example Patent	Example Patent Title
Trajectory 1	Cyber-physical machine tools	G05B × (B21 − B24)	G05B 19/4093 2006.1 B23B 1/00 2006.1 G05B 19/4155 2006.1	WO/2020/136899 published in 2020	NUMERICAL CONTROL DEVICE AND MACHINE LEARNING DEVICE
	Industrial Robots	G05B × B25J	G05B 19/19 B25J 9/16 B25J 9/00	20200164511 published in 2020	SERVO MOTION CONTROL METHOD AND APPARATUS AND ROBOT USING THE SAME
Trajectory 2	Robot machine tools	B25J × (B21 − B24)	B25J 15/04 B23Q 3/155 B23Q 3/16 B25J 9/08 B25J 15/00 B25J 19/04 B64F 5/00 B64G 1/00 B64G 4/00 B64G 99/00	EP3854536A1 published in 2021	ROBOTIC SERVICING MULTIFUNCTIONAL TOOL

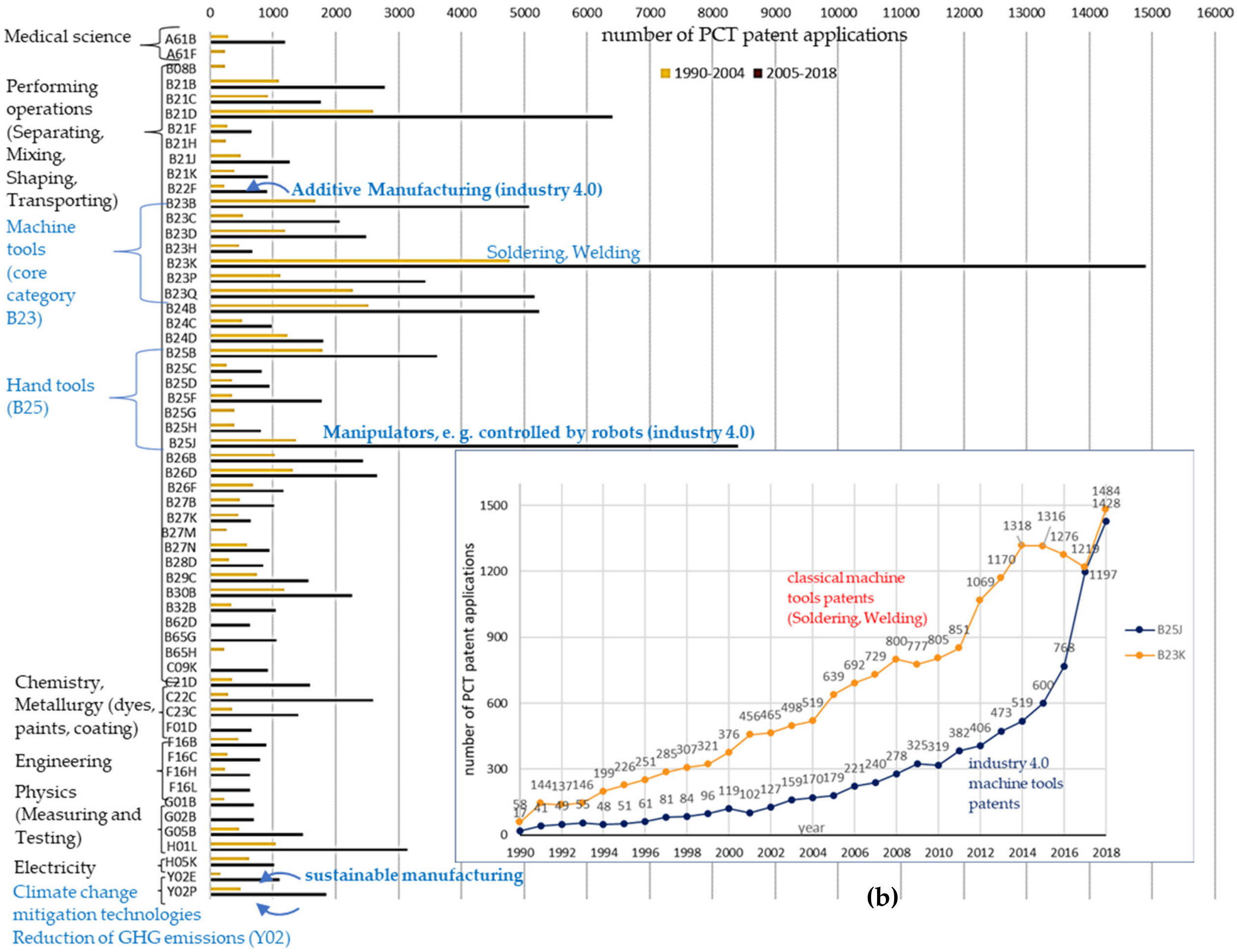
Source: Own representation by author based on WIPO Patentscope.

4.3. Incidence of Digital and Sustainable Technologies in Machine Tools Based on PCT Patents

As IPC subclasses related to sustainability categories are not amongst the top 100 co-occurrences, the results of a classification search of PCT patent applications in the open access database PATENTSCOPE of WIPO are presented in order to further support the results and shed light on overall tendencies in patenting (including sustainability categories) within the two timespans. This resulted in 2.67 million machine tools patent applications issued by all offices reporting to WIPO in the period 1990–2018, which has been narrowed down to 100.425 PCT patent applications (filtering for patent families is not yet feasible on PATENTSCOPE). The full search string can be found in Appendix C. Figure 6a displays the cumulative frequencies of IPC subclasses of patent applications in machine tools in the two time periods, 1990–2004 and 2005–2018, for comparison.

While almost all fields show higher patenting activity in the second timespan starting in 2005, two technological fields stand out in particular, namely B23K (Soldering or Unsoldering; Welding) with the highest number, and the already mentioned Industry 4.0 category B25J (Manipulators, Robots) with the second-highest number of PCT patents. Although the classical machine tools code B23K had the highest number of patent applications in both periods, and patent numbers in this category increased by a factor of three in the more recent time span, the Industry 4.0 category B25J (Manipulators, Robots) had the fastest increase of all trajectories in the second time span, with the number of PCT patents six times as high in 2005–2018 (8405 patents) compared to the previous period of 1990–2004 (1369 patents). In terms of total numbers, Industry 4.0 patenting in this category has been catching up with the highest filing category in both periods, B23K, since 2017 (Figure 6b).

Environment-related technologies are captured by category Y of the Cooperative Patent Classification (CPC), which focuses on technologies cutting across industry boundaries including sustainable technologies. Therefore, by definition, Y-patents of the CPC relate to externalities between industries jointly contributing to sustainability. Increasingly applied among the national and supranational patent offices involved, the USPTO and the EPO, the Y-category covers climate change mitigation technologies such as renewable energy generation and sustainable manufacturing [137], and "is becoming the de facto international standard for clean innovation studies" [138] (p. 24). The Y category was not part of the search string (see Appendix C). However, it is present in the data as classes Y02P and Y02E in the PATENTSCOPE sample (subdivisions of the Y-category) which refer to sustainable manufacturing, particularly climate change mitigation technologies in the production and processing of goods and the reduction of greenhouse gas emissions.



(**a**)

Figure 6. (**a**) Development of technological fields in machine tools, 1990–2004 (yellow) and 2005–2018 (black), measured as number of PCT patent applications by IPC subclass. Cumulative frequencies of IPC subclasses in machine tools based on 100.425 PCT patents (summing up patent numbers across IPC subclasses for the two time spans results in 151.253 patent applications due to patents being allocated to multiple IPC subclasses). For search string see Appendix C. A direct search for B22F and G05B results in a higher number of patents which, however, would have largely been outside the machine tools context. Time spans 1990–2004 (yellow) and 2005–2018 (black) are displayed for comparison. (**b**) Industry 4.0 machine tools patents closing the gap on most prevalent filing category; Source: own calculations based on WIPO Patentscope data retrieved on 23 December 2020 (**a**) and on 1 December 2021 (**b**).

Despite sustainability being a long-standing concept resonating with both science and practice since the end of the 1980s, and thus spanning the entire sample period, sustainable manufacturing in machine tools was found to be confined to a niche phenomenon compared to Industry 4.0, and is only beginning to achieve traction. As can be seen from the PATENTSCOPE sample, to date, patents in sustainable machine tools make up only a fraction of overall patenting in either time span. In climate change mitigation technologies (Y02P) (2.342) and reduction of greenhouse gas emissions (Y02E) (1.277), patent activity remains modest, with the numbers in brackets indicating the total number of PCT patents across the whole timespan of 1990–2018 (see last two rows of Figure 6a).

However, sustainable manufacturing patenting has risen substantially in the more recent time period in the PATENTSCOPE sample, with the number of PCT patents, particularly in climate change mitigation technologies (Y02P) nearly four times higher, and in the reduction of greenhouse gas emissions (Y02E) category more than six times higher in 2005–2018 then in the previous 15-year period. In sustainable technologies revolving around the working of metallic powder (B22F), comprising remanufacturing of articles from scrap or waste metal particles (B22F8/00) and additive manufacturing (B22F10/20), PCT patent numbers barely reach 1000 in the second time span, while jumping from 227 PCT patents to begin with to 913 in the more recent time span which, while accounting for only 1% of all patents, represents an increase by a factor of four. This recent sharp increase may be considered a silver lining indicating an imminent, if sluggish, smart sustainability transition in machine tools. Additive manufacturing, particularly 3D printing technology, which enables resource efficiency gains and therefore harbours the potential to reconcile economic with ecological sustainability, may act as a bridging technology between Industry 4.0 and sustainable manufacturing in machine tools.

To summarize, based on the FAMPAT sample, it has been shown that Industry 4.0-related externalities have entered the machine tools TIS by one of two trajectories: (1) cyber-physical machine tools and industrial robots, and (2) robot machine tools. While both trajectories testify to a smart transition underway within the machine tools TIS, they offer central pathways to a looming smart sustainability transition as well. Cyber-physical machine tools allow for a prolongation of the tool life cycle, while robotic machine tools (as demonstrated by the example of patent nr. EP3854536A1) contribute to sustainability through modularity and decreased energy consumption. The results of the PATENTSCOPE patent analysis confirm those of the previous FAMPAT patent analysis in that Industry 4.0 patenting has become a high-growth technology recently, with manipulators controlled by robots (B25J) the fastest-growing of all technologies in the second time span, that is, since 2005. By contrast, sustainable technologies such as remanufacturing and additive manufacturing remain confined to niches, although they do exhibit high growth rates over the past thirteen years.

As a result, from the TIS mapping and the two patent analyses it stands to reason that the machine tools TIS is increasingly becoming enmeshed in cyber-physical production systems and that a smart transition, which has been accelerating recently, and to a lesser degree a sustainability transition, have materialized within the last three decades in this core manufacturing sector.

5. Discussion

5.1. Main Insights

This paper contributes to understanding of the central technological pathways through which the digital transformation emerges in the mature sector of manufacturing, specifically machine tools, and of the way in which this emergence can contribute to sustainability. The results of the analyses provided above indicate, contrary to expectations, that a smart sustainability transition is currently not hampered by a lack of smart technologies; rather, at least to date, a greater hindrance is the sluggish introduction of sustainable machine tools. This is in line with prior work from other sectors; for instance, practitioners in the plastics industry have judged additive manufacturing to be of minor importance to the sustainability transition of their industry, instead highlighting the central role played by sensor and robot technologies [48]. These trajectories were found to be central pathways to a smart sustainability transition in this study as well.

In taking stock of the machine tools TIS over three decades with a focus on the latest two technological paradigm shifts, Industry 4.0 and sustainability, a multi-method approach has been employed covering TIS mapping gleaned from industry reports, scientific studies, and patent data and two patent analyses based on both a proprietary and a publicly available patent database (Questel's FAMPAT and WIPO PATENTSCOPE) in order to increase the objectivity and replicability of the results. This departs from current studies, in which literature surveys and case studies make up the majority [2], with a predominance of practitioner's reports on the one hand and a bias towards studies with a mere technological interest on the other [42].

The FAMPAT patent dataset was used to track externalities over a thirty year time span based on transnational "world market" patent families which, compared to triadic and PCT patents, have scarcely been employed in search strategies to date despite the reduction in geographical and market bias they offer. The latter is particularly important for TIS of global reach, such as machine tools, with the increasing market power of China and South Korea in particular. The methodology of measuring co-occurrences here was built on prior work by the OECD [98], with the methodological scope enlarged by application to the dynamics of a mature sector central to both the sustainable and digital transformations, rather than to emerging sectors. In addition, on a conceptual level a contribution to TIS theory is provided as neither externalities nor mature non-energy industries have been fundamentally centered in TIS studies thus far. In addressing externalities, the paper contributes to filling a long-standing research gap in TIS studies [33]. Specifically, externalities were directly measured rather than indirectly inferred from the existence of factors such as alliances and a shared labour pool [39], as TIS studies have previously done.

Results from the co-occurrence analysis indicate that externalities, particularly inter-industry externalities spilling over from monitoring and control systems (Physics) and semiconductors (Electricity) to classical machine tools, have increased considerably in the last thirteen years and are providing the engine of a smart sustainability transition. The sustainability trajectory in this transition, however, is just beginning to achieve traction.

5.2. Limitations

There are some limitations of this study which ought to be mentioned. The results of the patent analysis may be driven in part by the nature of the patent classification system. Co-occurrence of IPC classes as a proxy for the cross-fertilization of technologies may be overstated, as more recently emergent technologies tend to be represented in a wider set of IPC codes not as an expression of multidisciplinarity, but rather for the reason that there is not yet a specific IPC group at the date of filing [95]. Patent data reflect the current state of the IPC system, with longer standing categories accumulating more patents than more recent ones. Additive manufacturing, an important Industry 4.0 technology, for instance, has entered the IPC system only recently, as mirrored in codes B22F-1020 and B33Y, which were introduced as late as 2021 and 2015, respectively. Although there is a retrospective allocation of existing patent applications to newly created classes, it will take time before this technology category materializes, even though it has already been present in factual inventions in the machine tools TIS for some time. This is offset by the fact that newly introduced IPC codes tend to be used more intensely on account of their recent introduction or expansion [95].

The TIS map in this paper was gleaned from scientific studies, industry reports, and patent data; however, it did not include a stakeholder survey. The advantage of the approach taken here is that it allows for mapping of the overall development of the global machine tools TIS; however, this comes at the price of missing details on how the transition may be unfolding at the level of particular types of machines or regions.

5.3. Future Research Directions

In a follow-up study, it could be further investigated whether the still sluggish sustainability transition may be driven by machine tools remanufacturing initiatives in developing countries as an example of a catching up business model innovation, as well as what role ICT has to play in this transition. As the role of externalities has not been focused on in TIS studies thus far, further research should investigate externalities in other mature TIS, particularly in manufacturing, as this high energy usage sector is instrumental to both the sustainability transition and the digital transformation. The focus should lie on the measurement of externalities for which this study has proposed to employ patent co-occurrences, as well as on the interaction of externalities with other functions in a TIS context. Further studies could establish a link to parallel research streams from relational economic geography research [139], e.g., work on spillover effects [107], sector interactions [79], and connectivity [126]. The results of former studies on externalities in clusters may have to be reconsidered in the light of Industry 4.0, e.g., the interplay of cluster cohesion and centrifugal hollowing-out [140], as cohesion may become more difficult to maintain in cluster pipelines undergirded by blockchains in Industry 4.0 cyber-physical production systems [125].

6. Conclusions and Policy Implications

The paper has contributed to the sparse literature on the intersection between Industry 4.0 and sustainability, taking as an example machine tools, a manufacturing sector inextricably intertwined with other sectors such as ICT, electronics and automotive through inter-industry externalities stemming from intense producer–user interactions. Owing to the instrumentality of, in particular, metal-cutting, machine tools for both smart and sustainable manufacturing in the context of the European Ecodesign Directive and Industry 5.0, a highly relevant sector, was chosen for TIS mapping and ensuing patent co-occurrence analysis. The patent analysis illustrates the inalienability of manufacturing in reaching the UN SDGs in a more objective way, by means of patent data rather than by employing more elusive measures from reporting, a strategy suggested by van der Waal et al. [21].

The split result of this paper, namely that of a fast growing Industry 4.0 trajectory in the machine tools TIS and an underdeveloped sustainability trajectory, points to the need to better align the various Industry 4.0 policy and firm initiatives shown in the TIS map with all of the three sustainability dimensions, thus confirming earlier studies [6]. Current implementations such as cyber-physical production systems in machine tools are lopsided in their emphasis on the economic sustainability dimension, as ascertained in the TIS mapping analysis, in which economically driven Industry 4.0-related entrepreneurial activities and industrial policies have dominated without establishing linkages to green manufacturing despite the latter's existence since the 1990s and in spite of intense regulatory activities, e.g., the Circular Economy Action Plan of 2015. This one-track sustainability approach compromises the emergence of broad advocacy coalitions of machine tools manufacturers, ICT, and green manufacturing initiatives which could otherwise serve as vehicles for synergistic bottom-up policies promoting sustainability [141].

Two Industry 4.0 trajectories exhibiting inter-industry externalities were identified in the co-occurrence analysis of this paper: cyber-physical machine tools, which can contribute to longer tool life, and modular robot machine tools, which offer an increase in sustainability through lower energy consumption and increased efficiency and flexibility. Modular machine tools are an ideal use case reaching into both the economic and the ecological sphere; however, they have been addressed mainly from the economic angles of efficiency and flexibility thus far.

The prevalence of inter-industry instead of intra-industry externalities in the machine tools TIS, as demonstrated by the co-occurrence analysis for the period 1990–2018, has important implications for targeted policy measures. While intra-industry knowledge flows, e.g., between producers and users of metal-working machine tools and machine tools for grinding and sharpening, would call for specific research and development subsidies to reinforce this internal learning path, the inter-industry externalities dominating in the sample necessitate knowledge flows across industry boundaries, e.g., between ICT, electronics and machine tool makers, and call for more generic policy measures [142]. These generic policy measures should explicitly consider the interactions between a focal TIS, such as machine tools, and the context formed by other intruding TIS such as ICT or nudge it in new directions, such as toward sustainable technologies, with the aim of tapping into inter-industry externalities which provide unrelated knowledge and thus help to avoid lock-in [122].

For policy makers, the results obtained both from the TIS mapping and the two patent analyses underscore the need to unlock these inter-industry externalities by technology policies which cater not only to smart technologies, such as the programs Digital-jetzt in Germany and Made in China 2025 on a national level, and Cluster 4.0 on the European level, but to the confluence of smart and sustainable technologies such as additive manufacturing. Policy measures promoting inter-industry externalities, e.g., the German competitive cluster funding scheme InterClust (phased out by the end of 2021) should be reinforced given their centrality to extra-regional externalities which open up access to export pipelines particularly for small companies [122], which are numerous amongst machine tool companies worldwide. With policies targeted at inter-industry externalities, the TIS framework can be more soundly established as a policy tool, e.g., targeted at firms as coupling structures between the TIS and different, potentially conflicting contexts [79]. Machine tools companies are a prime example of such a coupling structure, as they must comply with divergent external demands such as, e.g., regulations promoting Industry 4.0 diffusion and servitization on the one hand and the wider societal priority shifts to more sustainable production and consumption modes which are accompanied by data security concerns on the other.

On a company level, the results can be used as a strategic analysis tool, helping to identify promising technological paths along the lines of platform diversification [15]. The two trajectories identified in the co-occurrence analysis underscore the need for traditional machine tool builders to tap into smart competencies through acquisitions, as in the case of the Swiss company Bystronic, which acquired the Spanish software company Kurago in 2021 with the aim of connecting their sheet metal processing machines to smart factories [143]. On the other hand, the underdeveloped sustainable trajectory may point to a window of opportunity opening towards new business models centering on the recycling, reuse and remanufacturing of machine tools, although the infrastructural (e.g., recycling and reuse infrastructure) and institutional setup (e.g., scalable Industry 4.0 platforms in the context of blockchains) is still immature. A middle-range strategy may include retrofitting of existing machinery, extending the use phase, and product-as-service business models targeted at functionality and accessibility rather than tangible machinery alone [144]. A higher rate of remanufacturing of machine tools which comes at the price of lower energy efficiency and Industry 4.0 platforms exacerbating the digital rebound effect are only two examples of sharp conflicts the machine tools TIS will be struggling with in the years to come. With the ecological and social impacts from large-scale industrial digitalization all but unequivocal, the one-track economic strategy visible in Industry 4.0-related research and development programs and patenting behaviour may entail a sustainability backlash along all dimensions in the long run. Inter-industry externalities need to be tapped into in order to achieve and perpetuate a truly smart sustainability transition.

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Appendix A. Patent Analysis to Identify Co-Occurrences between IPC Classes as a Measure of Externalities

FAMPAT (Questel's Orbit intelligence database) search strings:

Transnational 1990–2004:

(APD > 1989 AND APD < 2005) AND (WO/PC OR (EP/EPRC NOT WO/PC)) AND ((B21+ OR B23+ OR B24+ OR B26D+ OR B26F+ OR B27+ OR B30+ OR B25B+ OR B25C+ OR B25D+ OR B25F+ OR B25G+ OR B25H+ OR B25J+ OR B26B+)/IC/IPC/CPC/EC)

Transnational 2005–2018:

(APD > 2004 AND APD < 2019) AND (WO/PC OR (EP/EPRC NOT WO/PC)) AND ((B21+ OR B23+ OR B24+ OR B26D+ OR B26F+ OR B27+ OR B30+ OR B25B+ OR B25C+ OR B25D+ OR B25F+ OR B25G+ OR B25H+ OR B25J+ OR B26B+)/IC/IPC/CPC/EC)

Appendix B

Table A1. Concordance Table of Technological Fields and IPC Subclass Codes.

Technological Fields According to . . .			
IPC Section	**IPC Class**	**IPC Subclass**	**Subclass Code**
Electricity	Electric techniques not otherwise provided for	Printed circuits; casings or constructional details of electric apparatus; manufacture of assemblages of electrical components	H05K
	Basic electric elements	Semiconductor devices; electric solid state devices not otherwise provided for	H01L
Physics	Controlling, regulating (Industry 4.0)	Control or regulating systems in general; functional elements of such systems; monitoring or testing arrangements for such systems or elements (e. g., includes computer controlled systems and simulators (G05B15/00 and G05B17/00) embedded by means of digital processors (G05B19/042))	G05B
Chemistry and Metallurgy	Metallurgy, coating metallic material	Coating metallic material; coating material with metallic material; surface treatment of metallic material by diffusion into the surface, by chemical conversion or substitution; coating by vacuum evaporation, by sputtering, by ion implantation or by chemical vapour deposition, in general	C23C
	Metallurgy; ferrous or non-ferrous alloys; treatment of alloys or non-ferrous metals	Alloys	C22C
	Metallurgy of iron	Modifying the physical structure of ferrous metals; general devices for heat treatment of ferrous or non-ferrous metals or alloys; making metal malleable, e.g., by decarburisation, tempering or other treatments	C21D

Table A1. *Cont.*

Technological Fields According to ...			
IPC Section	**IPC Class**	**IPC Subclass**	**Subclass Code**
Performing Operations and Transporting	Layered Products	Layered products, i.e., products built-up of strata of flat or non-flat, e.g., cellular or honeycomb, form	B32B
	Hand Cutting Tools; Cutting; Severing	Hand-held cutting tools not otherwise provided for	B26B
	Hand tools; portable power-driven tools; handles for hand implements; workshop equipment; manipulators (Industry 4.0)	Manipulators; chambers provided with manipulation deviceswith manipulators covering "handling tools, devices, or machines [...] being controlled by means remote from the head, e.g., programme-controlled industrial robots" [134]	B25J
	Hand tools; portable power-driven tools; handles for hand implements; workshop equipment; manipulators	Combination or multi-purpose tools not otherwise provided for; details or components of portable power-driven tools not particularly related to the operations performed and not otherwise provided for	B25F
	Grinding, polishing	Tools for grinding, buffing, or sharpening	B24D
	Grinding, polishing	Machines, devices, or processes for grinding or polishing	B24B
	Machine tools; metal-working not otherwise provided for	Details, components, or accessories for machine tools, e.g., arrangements for copying or controlling	B23Q
	Machine tools; metal-working not otherwise provided for	Other working of metal; combined operations; universal machine tools	B23P
	Machine tools; metal-working not otherwise provided for	Soldering or Unsoldering; Welding; Cladding or Plating by Soldering or Welding; Cutting by applying heat locally, e.g., flame cutting; working by laser beam	B23K
	Machine tools; metal-working not otherwise provided for	Turning; boring	B23B
	Mechanical metalworking without essentially removing material; punching metal	Working or processing of sheet metal or metal tubes, rods, or profiles without essentially removing material; punching metal	B21D
	Mechanical metalworking without essentially removing material; punching metal	Rolling of metal	B21B

Source: own representation, Industry 4.0 related categories indicated in brackets; codes accessible at International Patent Classification (IPC) (wipo.int).

Appendix C. Patent Analysis of the Incidence of Digital and Sustainable Technologies in Machine Tools Based on PCT Patents

WIPO PATENTSCOPE search string:

IC: (B21B OR B21C OR B21D OR B21F OR B21G OR B21H OR B21J OR B21K OR B21L OR B23B OR B23C OR B23D OR B23F OR B23G OR B23H OR B23K OR B23P OR B23Q OR B24B OR B24C OR B24D OR B25B OR B25C OR B25D OR B25F OR B25G OR B25H OR B25J OR B26B OR B26D OR B26F OR B27B OR B27C OR B27D OR B27F OR B27G OR B27H OR B27J OR B27K OR B27L OR B27M OR B27N OR B30B) AND AD: [1990 TO 2018].

References

1. Wang, L.; Törngren, M.; Onori, M. Current status and advancement of cyber-physical systems in manufacturing. *J. Manuf. Syst.* **2015**, *37*, 517–527. [CrossRef]
2. Kamble, S.S.; Gunasekaran, A.; Gawankar, S.A. Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Saf. Environ. Prot.* **2018**, *117*, 408–425. [CrossRef]
3. Markard, J.; Raven, R.; Truffer, B. Sustainability transitions: An emerging field of research and its prospects. *Res. Policy* **2012**, *41*, 955–967. [CrossRef]
4. Pagoropoulos, A.; Pigosso, D.C.; McAloone, T.C. The Emergent Role of Digital Technologies in the Circular Economy: A Review. *Procedia CIRP* **2017**, *64*, 19–24. [CrossRef]
5. European Commission, Directorate-General for Research and Innovation; Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; Publications Office of the European Union: Luxembourg, 2021. Available online: https://data.europa.eu/doi/10.2777/308407 (accessed on 1 December 2021).
6. Müller, J.M.; Kiel, D.; Voigt, K.-I. What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. *Sustainability* **2018**, *10*, 247. [CrossRef]
7. Stock, T.; Obenaus, M.; Kunz, S.; Kohl, H. Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential. *Process Saf. Environ. Prot.* **2018**, *118*, 254–267. [CrossRef]
8. Furstenau, L.B.; Sott, M.K.; Kipper, L.M.; Machado, E.L.; Lopez-Robles, J.R.; Dohan, M.S.; Martin, M.J.C.; Zahid, A.; Abbasi, Q.H.; Imran, M.A. Link between sustainability and Industry 4.0: Trends, challenges and new perspectives. *IEEE Access* **2020**, *8*, 140079–140096. [CrossRef]
9. Chen, J.; Zhang, K.; Zhou, Y.; Liu, Y.; Li, L.; Chen, Z.; Yin, L. Exploring the Development of Research, Technology and Business of Machine Tool Domain in New-Generation Information Technology Environment Based on Machine Learning. *Sustainability* **2019**, *11*, 3316. [CrossRef]
10. Kristoffersen, E.; Blomsma, F.; Mikalef, P.; Li, J. The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *J. Bus. Res.* **2020**, *120*, 241–261. [CrossRef]
11. Kiel, D.; Müller, J.M.; Arnold, C.; Voigt, K.-I. Sustainable industrial value creation: Benefits and challenges of Industry 4.0. *Int. J. Innov. Manag.* **2017**, *21*, 1740015. [CrossRef]
12. Beier, G.; Niehoff, S.; Xue, B. More Sustainability in Industry through Industrial Internet of Things? *Appl. Sci.* **2018**, *8*, 219. [CrossRef]
13. Beier, G.; Ullrich, A.; Niehoff, S.; Reißig, M.; Habich, M. Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes—A literature review. *J. Clean. Prod.* **2020**, *259*, 120856. [CrossRef]
14. de Sousa Jabbour, A.B.L.; Jabbour, C.J.C.; Foropon, C.; Godinho Filho, M. When titans meet—Can Industry 4.0 revo-lutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technol. Forecast. Soc. Change* **2018**, *132*, 18–25. [CrossRef]
15. Verhoef, P.C.; Broekhuizen, T.; Bart, Y.; Bhattacharya, A.; Qi Dong, J.; Fabian, N.; Haenlein, M. Digital transformation: A multidisciplinary reflection and research agenda. *J. Bus. Res.* **2021**, *122*, 889–901. [CrossRef]
16. Cavada, M.; Rogers, C.D.F. Serious gaming as a means of facilitating truly smart cities: A narrative review. *Behav. Inf. Technol.* **2020**, *39*, 695–710. [CrossRef]
17. Horvath, A. CO_2 emission of Real Time Monitoring in China. In *Innovative Produkte und Dienstleistungen in der Mobilität*; Proff, H., Fojcik, T.M., Eds.; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2017; pp. 427–436, ISBN 978-3-658-18612-8.
18. Min, Y.-K.; Lee, S.-G.; Aoshima, Y. A comparative study on industrial spillover effects among Korea, China, the USA, Germany and Japan. *Ind. Manag. Data Syst.* **2019**, *119*, 454–472. [CrossRef]
19. Savastano, M.; Amendola, C.; Bellini, F.; D'Ascenzo, F. Contextual Impacts on Industrial Processes Brought by the Digital Transformation of Manufacturing: A Systematic Review. *Sustainability* **2019**, *11*, 891. [CrossRef]
20. Alcayaga, A.; Wiener, M.; Hansen, E.G. Towards a framework of smart-circular systems: An integrative literature review. *J. Clean. Prod.* **2019**, *221*, 622–634. [CrossRef]
21. van der Waal, J.W.; Thijssens, T.; Maas, K. The innovative contribution of multinational enterprises to the Sustainable Development Goals. *J. Clean. Prod.* **2021**, *285*, 125319. [CrossRef]
22. European Commission. Establishment of the Working Plan for 2009–2011 under the Ecodesign Directive: Communi-Cation from the Commission to the Council and the European Parliament. 2008. Available online: https://eur-lex.europa.eu/legal-content/en/HIS/?uri=CELEX:52008DC0660 (accessed on 1 December 2021).
23. Liu, C.; Xu, X. Cyber-physical Machine Tool—The Era of Machine Tool 4.0. *Procedia CIRP* **2017**, *63*, 70–75. [CrossRef]
24. Rosenberg, N. Technological Change in the Machine Tool Industry, 1840–1910. *J. Econ. Hist.* **1963**, *23*, 414–443. [CrossRef]
25. Lee, K.-R.; Suh, J.-H. Technology Gap Approach To A Dynamic Change In World Machine Tool Markets: A Panel Data Analysis. *Econ. Innov. New Technol.* **1998**, *7*, 203–220. [CrossRef]
26. Kalafsky, R.V. Examining the Global Machine Tool Industry: Transitions or Continuity? *Growth Change* **2016**, *47*, 138–156. [CrossRef]
27. Hall, B.H.; Ziedonis, R.H. The patent paradox revisited: An empirical study of patenting in the US semiconductor industry, 1979–1995. *Rand J. Econ.* **2001**, *32*, 101–128. [CrossRef]

28. Castellacci, F. Technological paradigms, regimes and trajectories: Manufacturing and service industries in a new taxonomy of sectoral patterns of innovation. *Res. Policy* **2008**, *37*, 978–994. [CrossRef]
29. Bresnahan, T.F. Technological change in ICT in light of ideas first learned about the machine tool industry. *Ind. Corp. Change* **2019**, *28*, 331–349. [CrossRef]
30. Chen, L.-C. Building extra-regional networks for regional innovation systems: Taiwan's machine tool industry in China. *Technol. Forecast. Soc. Change* **2015**, *100*, 107–117. [CrossRef]
31. Gertler, M.S. Worlds apart: The changing market geography of the German machinery industry. Small business economics: An entrepreneurship journal. *Small Bus. Econ.* **1996**, *8*, 87–106. [CrossRef]
32. Yeh, C.-C.; Chang, P.-L. The Taiwan system of innovation in the tool machine industry: A case study. *J. Eng. Technol. Manag.* **2003**, *20*, 367–380. [CrossRef]
33. Bergek, A. Technological Innovation System: A review of recent findings and suggestions for future research. In *Handbook of Sustainable Innovation*; Boons, F., McMeekin, A., Eds.; Edward Elgar Publishing Ltd.: Cheltenham, UK, 2019; pp. 200–218, ISBN 9781788112574.
34. Duguet, E.; MacGarvie, M. How well do patent citations measure flows of technology? Evidence from French innovation surveys. *Econ. Innov. New Technol.* **2005**, *14*, 375–393. [CrossRef]
35. Corsino, M.; Mariani, M.; Torrisi, S. Firm strategic behavior and the measurement of knowledge flows with patent citations. *Strateg. Manag. J.* **2019**, *40*, 1040–1069. [CrossRef]
36. Frietsch, R.; Schmoch, U. Transnational patents and international markets. *Scientometrics* **2010**, *82*, 185–200. [CrossRef]
37. Ulmanen, J.; Bergek, A. Influences of technological and sectoral contexts on Technological Innovation System. *Environ. Innov. Soc. Transit.* **2021**, *40*, 20–39. [CrossRef]
38. Markard, J. The life cycle of Technological Innovation System. *Technol. Forecast. Soc. Change* **2020**, *153*, 119407. [CrossRef]
39. Köhler, J.; Schade, W.; Leduc, G.; Wiesenthal, T.; Schade, B.; Tercero Espinoza, L. Leaving fossil fuels behind? An innovation system analysis of low carbon cars. *J. Clean. Prod.* **2013**, *48*, 176–186. [CrossRef]
40. Enyoghasi, C.; Badurdeen, F. Industry 4.0 for sustainable manufacturing: Opportunities at the product, process, and system levels. *Resour. Conserv. Recycl.* **2021**, *166*, 105362. [CrossRef]
41. Zeng, D.; Cao, H.; Jafar, S.; Tan, Y.; Su, S. A Life Cycle Ecological Sensitivity Analysis Method for Eco-Design Decision Making of Machine Tool. *Procedia CIRP* **2018**, *69*, 698–703. [CrossRef]
42. Hahn, F.; Jensen, S.; Tanev, S. Disruptive Innovation vs Disruptive Technology: The Disruptive Potential of the Value Propositions of 3D Printing Technology Startups. *Technol. Innov. Manag. Rev.* **2014**, *4*, 27–36. [CrossRef]
43. Liu, F.; Yin, J.; Cao, H.; He, Y. Investigations and practices on green manufacturing in machining systems. *J. Cent. South Univ. Technol.* **2005**, *12*, 18–24. [CrossRef]
44. Linder, M.; Sarasini, S.; van Loon, P. A Metric for Quantifying Product-Level Circularity. *J. Ind. Ecol.* **2017**, *21*, 545–558. [CrossRef]
45. Yeo, Z.; Masi, D.; Low, J.S.C.; Ng, Y.T.; Tan, P.S.; Barnes, S. Tools for promoting industrial symbiosis: A systematic review. *J. Ind. Ecol.* **2019**, *23*, 1087–1108. [CrossRef]
46. Chen, J.L.; Shen, I.-T.; Huang, H.-C. Energy saving innovative design of green machine tools by case-based reason-ing. In Proceedings of the 11th Global Conference on Sustainable Manufacturing: Innovative Solutions, Berlin, Germany, 23–25 September 2013; Seliger, G., Ed.; Universitätsverlag University of Technology Berlin: Berlin, Germany, 2013; pp. 419–423, ISBN 978-3-7983-2609-5.
47. Wit, B.; Pylak, K. Implementation of triple bottom line to a business model canvas in reverse logistics. *Electron Mark.* **2020**, *30*, 679–697. [CrossRef]
48. Nara, E.O.B.; da Costa, M.B.; Baierle, I.C.; Schaefer, J.L.; Benitez, G.B.; do Santos, L.M.A.L.; Benitez, L.B. Expected impact of Industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry. *Sustain. Prod. Consum.* **2021**, *25*, 102–122. [CrossRef]
49. Jeon, B.; Yoon, J.-S.; Um, J.; Suh, S.-H. The architecture development of Industry 4.0 compliant smart machine tool system (SMTS). *J. Intell. Manuf.* **2020**, *31*, 1837–1859. [CrossRef]
50. Möhring, H.-C.; Brecher, C.; Abele, E.; Fleischer, J.; Bleicher, F. Materials in machine tool structures. *CIRP Ann.* **2015**, *64*, 725–748. [CrossRef]
51. Bugert, N.; Lasch, R. Supply chain disruption models: A critical review. *Logist. Res.* **2018**, *11*, 1–35. [CrossRef]
52. Tait, K.; Gereffi, G. Remanufacturing Services in the Construction Machinery Value Chain. In *Services in Global Value Chains: Manufacturing-Related Services*; Low, P., Pasadilla, G.O., Eds.; World Scientific: Singapore, 2016; pp. 412–440, ISBN 9789813141452.
53. Peukert, B.; Benecke, S.; Clavell, J.; Neugebauer, S.; Nissen, N.F.; Uhlmann, E.; Lang, K.-D.; Finkbeiner, M. Addressing Sustainability and Flexibility in Manufacturing Via Smart Modular Machine Tool Frames to Support Sustainable Value Creation. *Procedia CIRP* **2015**, *29*, 514–519. [CrossRef]
54. Silva, D.A.L.; Firmino, A.S.; Ferro, F.S.; Christoforo, A.L.; Leite, F.R.; Lahr, F.A.R.; Kellens, K. Life cycle assessment of a hot-pressing machine to manufacture particleboards: Hotspots, environmental indicators, and solutions. *Int. J. Life Cycle Assess.* **2020**, *25*, 1059–1077. [CrossRef]
55. Tsuji, M. Technological innovation and the formation of Japanese technology: The case of the machine tool industry. *AI Soc.* **2003**, *17*, 291–306. [CrossRef]
56. Gao, R.X.; Wang, P. Through Life Analysis for Machine Tools: From Design to Remanufacture. *Procedia CIRP* **2017**, *59*, 2–7. [CrossRef]

57. Fuchs, M. Arbeit in Industrie 4.0—Regionale Unterschiede, räumliche Abhängigkeiten, Place-Making. *Arb.-Und Ind. Stud.* **2019**, *12*, 57–72.
58. Fuchs, M. Does the Digitalization of Manufacturing Boost a 'Smart' Era of Capital Accumulation? *Z. Wirtsch.* **2020**, *64*, 47–57. [CrossRef]
59. Bresnahan, T.F.; Trajtenberg, M. General purpose technologies 'Engines of growth'? *J. Econom.* **1995**, *65*, 83–108. [CrossRef]
60. Shea, C.M.; Grinde, R.; Elmslie, B. Nanotechnology as general-purpose technology: Empirical evidence and implications. *Technol. Anal. Strateg. Manag.* **2011**, *23*, 175–192. [CrossRef]
61. Kerbrat, O.; Le Bourhis, F.; Mognol, P.; Hascoët, J.-Y. Environmental Impact Assessment Studies in Additive Manufacturing. In *Handbook of Sustainability in Additive Manufacturing*; Muthu, S.S., Savalani, M.M., Eds.; Springer: Singapore, 2016; pp. 31–63, ISBN 978-981-10-0604-3.
62. Apostolos, F.; Panagiotis, S.; Konstantinos, S.; George, C. Energy Efficiency Assessment of Laser Drilling Process. *Phys. Procedia* **2012**, *39*, 776–783. [CrossRef]
63. Ford, S.; Despeisse, M. Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *J. Clean. Prod.* **2016**, *137*, 1573–1587. [CrossRef]
64. Ghobadian, A.; Talavera, I.; Bhattacharya, A.; Kumar, V.; Garza-Reyes, J.A.; O'Regan, N. Examining legitimatisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability. *Int. J. Prod. Econ.* **2020**, *219*, 457–468. [CrossRef]
65. Kellens, K.; Mertens, R.; Paraskevas, D.; Dewulf, W.; Duflou, J.R. Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing? *Procedia CIRP* **2017**, *61*, 582–587. [CrossRef]
66. Kianinejad, K.; Uhlmann, E.; Peukert, B. Investigation into Energy Efficiency of Outdated Cutting Machine Tools and Identification of Improvement Potentials to Promote Sustainability. *Procedia CIRP* **2015**, *26*, 533–538. [CrossRef]
67. Diaz, N.; Choi, S.; Helu, M.; Chen, Y.; Jayanathan, S.; Yasui, Y. Machine Tool Design and Operation Strategies for Green Manufacturing. 2010. Available online: https://escholarship.org/uc/item/5gz7j6rn (accessed on 24 August 2020).
68. van der Panne, G. Agglomeration externalities: Marshall versus Jacobs. *J. Evol. Econ. JEE* **2004**, *14*, 593–604. [CrossRef]
69. Marshall, A. *Principles of Economics*; Macmillan: London, UK, 1890.
70. Jacobs, J. *The Economy of Cities*; 2 Printing; Random House: New York, NY, USA, 1969.
71. Bergek, A.; Jacobsson, S. The emergence of a growth industry: A comparative analysis of the German, Dutch and Swedish wind turbine industries. In *Change, Transformation and Development*; Metcalfe, J.S., Cantner, U., Eds.; Physica-Verlag HD: Heidelberg, Germany, 2003; pp. 197–227, ISBN 978-3-642-62410-0.
72. Bergek, A.; Jacobsson, S.; Carlsson, B.; Lindmark, S.; Rickne, A. Analyzing the functional dynamics of Technological Innovation System: A scheme of analysis. *Res. Policy* **2008**, *37*, 407–429. [CrossRef]
73. Grossman, G.M.; Helpman, E. Trade, knowledge spillovers, and growth. *Eur. Econ. Rev. EER* **1991**, *35*, 517–526. [CrossRef]
74. Frenken, K.; van Oort, F.G.; Verburg, T. Related variety, unrelated variety and regional economic growth. *Reg. Stud.* **2007**, *41*, 685–697. [CrossRef]
75. Hansen, T.; Coenen, L. The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environ. Innov. Soc. Transit.* **2015**, *17*, 92–109. [CrossRef]
76. Markard, J.; Bento, N. Accelerating Transitions—New Challenges and Lessons for Research. In Proceedings of the 4th NEST Conference, Lisbon, Portugal, 5 April 2019. Available online: https://ethz.ch/content/dam/ethz/special-interest/mtec/sustainability-and-technology/PDFs/Acceleration%204thNEST.pdf (accessed on 1 December 2021).
77. Hekkert, M.P.; Negro, S.O. Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technol. Forecast. Soc. Change* **2009**, *76*, 584–594. [CrossRef]
78. Johnson, A.; Jacobsson, S. Inducement and Blocking Mechanisms in the Development of a New Industry: The Case of Renewable Energy Technology in Sweden. In *Technology and the Market: Demand, Users and Innovation*; Coombs, R., Green, K., Walsh, V., Richard, A., Eds.; Edward Elgar Publishing Ltd.: Cheltenham, UK; Northhampton, MA, USA, 2001; pp. 89–111.
79. Bergek, A.; Hekkert, M.; Jacobsson, S.; Markard, J.; Sandén, B.; Truffer, B. Technological Innovation System in contexts: Conceptualizing contextual structures and interaction dynamics. *Environ. Innov. Soc. Transit.* **2015**, *16*, 51–64. [CrossRef]
80. Bergek, A.; Jacobsson, S.; Sandén, B.A. 'Legitimation' and 'development of positive externalities': Two key processes in the formation phase of Technological Innovation System. *Technol. Anal. Strateg. Manag.* **2008**, *20*, 575–592. [CrossRef]
81. Yap, X.-S.; Truffer, B. Shaping selection environments for industrial catch-up and sustainability transitions: A systemic perspective on endogenizing windows of opportunity. *Res. Policy* **2019**, *48*, 1030–1047. [CrossRef]
82. Pittino, D.; Visintin, F.; Compagno, C. Front end innovation and stakeholder involvement in machine tools sector. *IJEIM* **2011**, *14*, 96–112. [CrossRef]
83. Cappelli, R.; Czarnitzki, D.; Kraft, K. Sources of spillovers for imitation and innovation. *Res. Policy* **2014**, *43*, 115–120. [CrossRef]
84. Oh, E.-T.; Chen, K.-M.; Wang, L.-M.; Liu, R.-J. Value creation in regional innovation systems: The case of Taiwan's machine tool enterprises. *Technol. Forecast. Soc. Change* **2015**, *100*, 118–129. [CrossRef]
85. Gordon, R.; Krieger, J. Investigating Differentiated Production Systems: The U.S. Machine Tool Industry. *Compet. Change* **1998**, *3*, 41–67. [CrossRef]
86. Porter, A.L.; Garner, J.; Carley, S.F.; Newman, N.C. Emergence scoring to identify frontier R&D topics and key players. *Technol. Forecast. Soc. Change* **2019**, *146*, 628–643. [CrossRef]

87. Machado, C.G.; Winroth, M.P.; Ribeiro da Silva, E.H.D. Sustainable manufacturing in Industry 4.0: An emerging research agenda. *Int. J. Prod. Res.* **2020**, *58*, 1462–1484. [CrossRef]
88. Börner, K.; Polley, D.E. Replicable Science of Science Studies. In *Measuring Scholarly Impact*; Ding, Y., Rousseau, R., Wolfram, D., Eds.; Springer International Publishing: Cham, Switzerland, 2014; ISBN 978-3-319-10376-1.
89. Boyack, K.W.; Klavans, R. Measuring science–technology interaction using rare inventor–author names. *J. Informetr.* **2008**, *2*, 173–182. [CrossRef]
90. Berg, S.; Wustmans, M.; Bröring, S. Identifying first signals of emerging dominance in a Technological Innovation System: A novel approach based on patents. *Technol. Forecast. Soc. Change* **2019**, *146*, 706–722. [CrossRef]
91. Kalthaus, M. Identifying technological sub-trajectories in patent data: The case of photovoltaics. *Econ. Innov. New Technol.* **2019**, *28*, 407–434. [CrossRef]
92. Leydesdorff, L.; Alkemade, F.; Heimeriks, G.; Hoekstra, R. Patents as instruments for exploring innovation dynamics: Geographic and technological perspectives on “photovoltaic cells”. *Scientometrics* **2015**, *102*, 629–651. [CrossRef]
93. de Rassenfosse, G.; Dernis, H.; Guellec, D.; Picci, L.; van Pottelsberghe de Potterie, B. The worldwide count of prior-ity patents: A new indicator of inventive activity. *Res. Policy* **2013**, *42*, 720–737. [CrossRef]
94. Dernis, H.; Khan, M. *Triadic Patent Families Methodology: OECD Science, Technology and Industry Working Papers*; OECD Publishing: Paris, France, 2004.
95. Dernis, H.; Squicciarini, M.; de Pinho, R. Detecting the emergence of technologies and the evolution and co-development trajectories in science (DETECTS): A ‘burst’ analysis-based approach. *J. Technol. Transf.* **2016**, *41*, 930–960. [CrossRef]
96. Lizin, S.; Leroy, J.; Delvenne, C.; Dijk, M.; de Schepper, E.; van Passel, S. A patent landscape analysis for organic photovoltaic solar cells: Identifying the technology’s development phase. *Renew. Energy* **2013**, *57*, 5–11. [CrossRef]
97. Abbas, A.; Zhang, L.; Khan, S.U. A literature review on the state-of-the-art in patent analysis. *World Pat. Inf.* **2014**, *37*, 3–13. [CrossRef]
98. OECD (Ed.) *OECD Science, Technology and Industry Scoreboard 2013*; OECD Publishing: Paris, France, 2013.
99. Grupp, H. Spillover effects and the science base of innovations reconsidered: An empirical approach. *J. Evol. Econ. JEE* **1996**, *6*, 175–197. [CrossRef]
100. Leydesdorff, L.; Kushnir, D.; Rafols, I. Interactive overlay maps for US patent (USPTO) data based on International Patent Classification (IPC). *Scientometrics* **2014**, *98*, 1583–1599. [CrossRef]
101. Würmseher, M.; Firmin, L. Nanobiotech in big pharma: A business perspective. *Nanomedicine* **2017**, *12*, 535–543. [CrossRef]
102. Leydesdorff, L.; Kogler, D.F.; Yan, B. Mapping patent classifications: Portfolio and statistical analysis, and the comparison of strengths and weaknesses. *Scientometrics* **2017**, *112*, 1573–1591. [CrossRef]
103. Hall, B.; Jaffe, A.; Trajtenberg, M. The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools, Cambridge, MA, 2001. NBER Working Paper No. 8498. Available online: https://www.nber.org/papers/w8498 (accessed on 1 December 2021).
104. Jaffe, A.B.; de Rassenfosse, G. Patent citation data in social science research: Overview and best practices. *J. Assoc. Inf. Sci. Technol.* **2017**, *68*, 1360–1374. [CrossRef]
105. Carlsson, B.; Stankiewicz, R. On the nature, function and compostion of technological systems. *J. Evol. Econ.* **1991**, *1*, 93–118. [CrossRef]
106. Edquist, C. Systems of Innovation: Perspectives and Challenges. In *The Oxford Handbook of Innovation*; Fagerberg, J., Mowery, D.C., Eds.; Oxford University Press: Oxford, UK, 2006; pp. 181–208.
107. Hekkert, M.P.; Suurs, R.; Negro, S.O.; Kuhlmann, S.; Smits, R. Functions of innovation systems: A new approach for analysing technological change. *Technol. Forecast. Soc. Change* **2007**, *74*, 413–432. [CrossRef]
108. Planko, J.; Cramer, J.; Hekkert, M.P.; Chappin, M.M. Combining the Technological Innovation System framework with the entrepreneurs’ perspective on innovation. *Technol. Anal. Strateg. Manag.* **2017**, *29*, 614–625. [CrossRef]
109. Bloom, N.; Schankerman, M.; van Reenen, J. Identifying Technology Spillovers and Product Market Rivalry. *Econometrica* **2013**, *81*, 1347–1393. [CrossRef]
110. Graham, J. Firm and state strategy in a multipolar world: The changing geography of machine tool production and trade. In *Trading Industries, Trading Regions: International Trade, American Industry, and Regional Economic Development*; Noponen, H., Graham, J., Markusen, A.R., Eds.; Guilford Press: New York, NY, USA, 1993; pp. 140–174, ISBN 0-89862-296-4.
111. Stephenson, D. Machine Tools the Mother Machines: A Collaborative Approach to Standardization. Available online: https://www.bsigroup.com/en-GB/blog/manufacturing-blog/machine-tools-the-mother-machines/ (accessed on 1 December 2021).
112. Boeing, P.; Mueller, E. Measuring patent quality in cross-country comparison. *Econ. Lett.* **2016**, *149*, 145–147. [CrossRef]
113. Hallward-Driemeier, M.; Nayyar, G. Trouble in the Making: The Future of Manufacturing-Led Development, Washington. 2018. Available online: 10.1596/978-1-4648-1174-6 (accessed on 20 August 2020).
114. Dang, J.; Motohashi, K. Patent statistics: A good indicator for innovation in China? Patent subsidy program impacts on patent quality. *China Econ. Rev.* **2015**, *35*, 137–155. [CrossRef]
115. World Intellectual Property Organization. WIPO Statistics Database. Available online: https://www3.wipo.int/ipstats/index.htm (accessed on 27 October 2020).
116. Patel, P.; Pavitt, K. The technological competencies of the world’s largest firms: Complex and path-dependent, but not much variety. *Res. Policy* **1997**, *26*, 141–156. [CrossRef]

117. Tassey, G. Standards and expansion paths in high-tech industries. In *Handbook of Innovation and Standards*; Hawkins, R., Blind, K., Page, R., Eds.; Edward Elgar Publishing Ltd.: Cheltenham, UK; Northhampton, MA, USA, 2017; pp. 135–161, ISBN 9781783470082.
118. *Guide to Application of the Machinery Directive 2006/42/EC*; European Commission: Brussels, Belgium, 2019. Available online: https://ec.europa.eu/docsroom/documents/38022 (accessed on 1 December 2021).
119. CECIMO. Is the Machinery Directive Fit for Pose? 2020. Available online: https://www.cecimo.eu/wp-content/uploads/2020/07/CECIMO-Position-Paper-Is-the-Machinery-Directive-fit-for-purpose.pdf (accessed on 1 December 2021).
120. BDI the Voice of German Industry. E-Privacy Regulation: German Industry's Recommendations for the Trialogue. 2021. Available online: https://english.bdi.eu/publication/news/e-privacy-regulation/ (accessed on 1 December 2021).
121. Korea Chamber of Commerce and Industry. Industry Innovation 3.0. 2014. Available online: http://www.apo-tokyo.org/publications/wp-content/uploads/sites/5/2014_Jul-Aug_p8.pdf#:~{}:text=Industry%20Innovation%203.0%20%28II%203.0%29%20that%20focuses%20on,small%20companies%20is%20essential%20for%20sustainable%20economic%20growth (accessed on 1 December 2021).
122. Dohse, D.; Fornahl, D.; Vehrke, J. Fostering place-based innovation and internationalization—The new turn in German technology policy. *Eur. Plan. Stud.* **2018**, *26*, 1137–1159. [CrossRef]
123. Global Trade Alert. Available online: https://www.globaltradealert.org/sector/442/period-from_20080101/period-to_20200820/product_8456,8457,8458,8459,8460,8461,8462,8463,8464,8465/day-to_0820 (accessed on 5 July 2021).
124. Dosi, G. Technological paradigms and technological trajectories. *Res. Policy* **1982**, *11*, 147–162. [CrossRef]
125. Min, H. Blockchain technology for enhancing supply chain resilience. *Bus. Horiz.* **2019**, *62*, 35–45. [CrossRef]
126. Lee, A.; Mudambi, R.; Cano-Kollmann, M. An analysis of Japan's connectivity to the global innovation system. *MBR* **2016**, *24*, 399–423. [CrossRef]
127. Simmons, E.S. "Black sheep" in the patent family. *World Pat. Inf.* **2009**, *31*, 11–18. [CrossRef]
128. Orbit Intelligence Knowledge Base. FAMPAT Family Construction Rules. Available online: https://intelligence.help.questel.com/en/support/solutions/articles/77000436698-fampat-family-construction-rules (accessed on 1 December 2021).
129. Schmoch, U. Concept of a Technology Classification for Country Comparisons: Final Report to the World Intellectual Property Organisation (WIPO). 2008. Available online: http://www.wipo.int/export/sites/www/ipstats/en/statistics/patents/pdf/wipo_ipc_technology.pdf (accessed on 1 December 2021).
130. VDW. Auftragseingang in der Deutschen Werkzeugmaschinenindustrie Hat Sich Aktuell Etwas Gefangen. 2019. Available online: https://vdw.de/wp-content/uploads/2019/11/pm_ae_q3_2019_2019-11-13.pdf (accessed on 1 December 2021).
131. Zein, A. *Transition towards Energy Efficient Machine Tools*; Springer: Berlin/Heidelberg, Germany, 2012; ISBN 978-3-642-32246-4.
132. Baruffaldi, S.; van Beuzekom, B.; Dernis, H.; Harhoff, D.; Rao, N.; Rosenfeld, D.; Squicciarini, M. Identifying and measuring developments in artificial intelligence: Making the impossible possible. *OECD Sci. Technol. Ind. Work.* **2020**. [CrossRef]
133. Hoeren, T. The Semiconductor Chip Industry—The History, Present and Future of Its IP Law Framework. *IIC* **2016**, *47*, 763–796. [CrossRef]
134. World Intellectual Property Organization. WIPO IP Portal: Manipulators. Available online: https://www.wipo.int/classifications/ipc/ipcpub/?notion=scheme&version=20200101&symbol=B25J&menulang=en&lang=en&viewmode=f&fipcpc=no&showdeleted=yes&indexes=no&headings=yes&notes=yes&direction=o2n&initial=A&cwid=none&tree=no&searchmode=smart (accessed on 1 December 2021).
135. Sagasaki, M.; Kumazawa, T. Numerical Control Device and Machine Learning Device, 28 December 2018. Available online: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2020136899&_cid=P11-KWF56G-04864-1 (accessed on 1 December 2021).
136. Roberts, P.; Bratsberg, S.; Rago, J. Robot Servicing Multifunctional Tool, 15 October 2012. Available online: https://patentimages.storage.googleapis.com/6b/51/51/b6409601cdfd83/EP3854536A1.pdf (accessed on 1 December 2021).
137. OECD. Patent Search Strategies for the Identification of Selected Environment-Related Technologies (ENV-TECH). Available online: https://www.oecd.org/environment/consumption-innovation/ENV-tech%20search%20strategies,%20version%20for%20OECDstat%20 (accessed on 1 December 2021).
138. Rudyk, I.; Owens, G.; Volpe, A.; Ondhowe, R. Climate Change Mitigation Technologies in Europe: Evidence from Patent and Economic Data 978-3-89605-145-5, Nairobi, Munich. 2015. Available online: www.epo.org/climate-europe (accessed on 1 December 2021).
139. Bathelt, H.; Gluckler, J. Toward a relational economic geography. *J. Econ. Geogr.* **2003**, *3*, 117–144. [CrossRef]
140. Bathelt, H.; Malmberg, A.; Maskell, P. Clusters and knowledge: Local buzz, global pipelines and the process of knowledge creation. *Prog. Hum. Geogr.* **2004**, *28*, 31–56. [CrossRef]
141. European Cluster Observatory. Cluster4Smart: Cluster Management Abilities, Capacities, Skills and Competences towards a Smart Industry (Cluster 4.0 and Industry 4.0) Intellectual Output 1. 2018. Available online: https://cluster4smart.eu/files/Cluster4Smart_IO1_Study_full_EN.pdf (accessed on 1 December 2021).
142. Noailly, J.; Shestalova, V. Knowledge spillovers from renewable energy technologies: Lessons from patent cita-tions. *Environ. Innov. Soc. Transit.* **2017**, *22*, 1–14. [CrossRef]
143. Bystronik Laser, A.G. Bystronik Acquires Software Specialist. Available online: https://www.bystronic.com/en/news/in-depth/bystronic-acquires-software-specialist-kurago.php (accessed on 1 December 2021).
144. Stock, T.; Seliger, G. Opportunities of Sustainable Manufacturing in Industry 4.0. *Procedia CIRP* **2016**, *40*, 536–541. [CrossRef]