Sorcery at the Technical Frontier:
How Embedded Knowledge on the Production Line Can Give Workers a Role in Innovation

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Executive Summary:

Technological change in the United States has historically been associated with significant changes in skill and labor demand across the economy, with strong patterns of displacement and skill demand polarization in the manufacturing sector (Autor and Dorn 2013; Goos et al 2014). Workers can view technological change as a threat to their employment or that of future generations, leading to frustration or fear (Ananat et al 2017). In this paper, we draw on qualitative evidence from leading-edge firms and organizations in the optoelectronics industry to identify organizational characteristics associated with manufacturing worker participation in innovation, which may present an alternative to the passive or adversarial experience of many workers with respect to technological change. We identify possible firm-level mechanisms for generating greater worker scope of influence in the innovation process and discuss potential policy implications and further work. We find that firms in our sample which are more vertically integrated (outsource less) from design to production exhibit a greater tendency to interface between technology developers and production workers, and in turn we propose that this may give workers a greater influence over how their work will evolve. We find also in our sample that firms on the experimental leading-edge of process innovation, with limited theoretical foundations, relied on experiential knowledge (for production and technology design workers) to support development, making production workers local experts on the highly sensitive "black-box" characteristics of specific equipment or processes. These observations suggest that firm structure and technical certainty could influence the role and influence of workers as participants in technological change. Firm structure especially can be influenced by capital and geographic considerations, which may provide scope for policy oriented toward worker experience.

1. Introduction:

Manufacturing in the US is affected by powerful economic forces – including globalization and technological change – that have dramatically changed labor market outcomes for workers. The U.S.'s manufacturing value added grew by $587 billion (40%) from 1999 to 2014 (World Bank); however, since the mid-1980s, the number of U.S. manufacturing employees manufacturing has declined (U.S. Bureau of Labor Statistics). Scholars have tried to pinpoint the source of this trend – to offshoring, automation, or both – but none have done so definitively (Autor and Dorn 2013; Goos et al 2014). Overall, across all industries there has been a polarization of labor demand with more jobs at the top and at the bottom of the income distribution and relatively fewer in the middle (U.S. Bureau of Labor Statistics). Technical change due to emerging technologies can directly alter the demand for worker skills (Combemale, Whitefoot, Ales and Fuchs 2020) and may thus further accelerate these trends.[1]

Manufacturing, in addition to being strongly affected by technological change, is a significant epicenter of industrial research and development activity, accounting for 66% of Industrial R&D spending in the United States in 2015 (NSF 2018). This interaction of innovation and sectoral change raises the question of what role workers currently have or may have in process of innovation. With continued technological change a major part in potentially unstable or uncertain employment conditions for many

[1] Significant literature exists on skill-biased technological change and its influence on employment, wages, international trade, and productivity (Autor et al 2003; Card and DiNardo 2002; Bartel et al 2007; Acemoglu and Restrepo 2017). Research, however, has been limited in its ability to directly measure different types of simultaneous technology change, and their possible relation to labor demand. The current approach in economics linking technical change and labor outcomes (c.f. Ales, Kurnaz, Sleet 2015) is mostly retrospective and top-down: dependent on aggregate historical data, it focuses on past episodes of technical change and works largely with coarse groups of workers ranked by historic occupational wages (Card and Dinardo 2002; Bresnahan and Brynjolfsson 2002; Autor, Levy and Murnane 2003; Acemoglu and Autor 2011; Pedro and Lee 2011; Autor and Dorn 2013). Traditional quantitative approaches may not be adaptive to technological or policy changes that displace firm behavior outside of a narrow band of historic factor substitutions captured by statistical data (Chenery 1949; Lave 1966; Pearl and Enos 1975; Wibe 1984; Smith 1986). Such limitations present challenges in anticipating the effects of emerging technologies on labor outcomes, complicating policy efforts to mitigate associated labor market failures.

workers, especially over the long term (Brynjolfsson, Mitchell and Rock 2018), and common feelings of frustration and helplessness in the face of perceived future technological placement (Ananat et al 2017), a participatory role for workers in innovation offers an important contrast and potential alternative to a passive or adversarial labor experience of technology change.

In this report, we present qualitative insights from the optoelectronics industry on different innovation arrangements and the roles that these allow (or prevent) for production workers as participants in technological change. We identify organizational characteristics surrounding these arrangements and suggest mechanisms within firms which may generate more participatory roles in innovation for workers. We then provide a discussion of potential policy directions and needed future work to develop our findings.

2. Literature Review

The level of vertical integration by a firm is informative in anticipating the scope of innovation in which the firm (and its workers) may participate.

The structure of a design architecture or of a firm have related implications for innovation outcomes. In the modularity literature, modularized designs allow local, more incremental innovation to occur while affecting only the elements of a single module, while more significant innovations may need to cross module boundaries, with greater associated costs (Baldwin and Clark 2000). This conceptualization links naturally with the theory of the firm, shifting modular boundaries for interfirm boundaries: a disaggregated value chain may be able to host incremental innovations, but costs are incurred when transacting across the chain (Chandler 1993), potentially impairing the returns to innovation, and in particular imperfect contracts will impose costs for innovation involving multiple elements of the value chain (Antras 2005).

Firms' level of integration may also influence access to knowledge: if issues in innovation occur outside of the firm's scope of activity, it must obtain and manage knowledge from elsewhere. However, the more uncertain the technical circumstances, the more tacit the knowledge and the more difficult (or costly) it will be to transfer across the firm boundary, and the more uncertain the firms' investments in innovation (Chesbrough 2004).

Existing linkages between structure and innovation are informative in thinking about the possibility space for worker participation. However, the literature has not generally linked the role of workers in innovation to firm structure. In this report, we build on the innovation literature by examining a multilateral association among workers, innovation, and firm structure. We show how firm structure may alter the possible interactions between workers and innovation happening outside their role, and hence the scope for their participation.

3. Methods:

This report draws on grounded theory-building principles (Glasner and Strauss, 1967; Eisenhardt, 1989; Yin 1989) to explore associations between the role of production workers in innovation and characteristics of firms employing them. We draw on qualitative evidence from a case study that we conducted of the optoelectronics industry at a time of ongoing but heterogeneous technological change across the industry.[2] Our results draw primarily on over 30 semi-structured interviews with employees at 12 different firms and organizations in the industry across the United States, Europe and East Asia, covering every step of transceiver production as well as product and process development (the device manufacturers accounted for 42-44% of industry volume at the time of our study). Our firm sample captured the range of technological variation in the industry, allowing us to contrast mature technologies with efforts at the technical frontier: broadly we observed variation in two central technologies – automation (substitution of machines for workers), consolidation (formerly discrete parts replaced by a single part with their collective functions).

[2] See Combemale, Whitefoot, Ales and Fuchs 2020 for our quantitative work on this same industry around the labor implications of different technologies.

We spoke to engineers, senior technical officers, trainers, supervisors, and operators: our broad sample allowed us to capture the content and scope of production work and characterize the interface between workers and technological development in-house at each firm. In addition to interviews, we performed line observations across the production processes for five different optoelectronic device designs (three in the U.S. and two in Asia). The principal data for our subsequent qualitative analysis were the 1) types of technologies in use at each firm (along dimensions of consolidation and automation), 2) whether or not firm leaders considered their production processes to be technically well understood by engineers, 3) whether or not production workers were involved in process or product development, 4) whether or not there was equipment-specific knowledge that affected production outcomes, 5) firm geographic location (possibly varying between segments of the value chain under one firm), and 6) the organization of the firm, namely which segments of the industry value chain the firm occupied.

4. Case Industry and Sample Firms: Optoelectronics Manufacturing

Our case industry, optoelectronics, is forecast to reach $53 billion in global annual revenue in 2025 (MarketsandMarkets 2020): this industry, while a small subset of the $515 billion global semiconductor industry (Deloitte 2020), is both growing and sufficiently diversified to allow us to capture a variety of organizational types and technological regimes within our firm sample. The industry is distributed heavily across East Asia, India, the U.S., and Western Europe, with a value chain in four broad segments: component fabrication (and testing), component assembly into final product (and associated testing, subassembly, etc.), process design and product design. In the United States, all stages of the value chain are represented, though within our firm sample and the industry more broadly the U.S. has relatively more of the industry's product and process design sites than it does, for instance, assembly.

Optoelectronic devices combine electronic and photonic (optical) elements for a variety of applications, broadly in sensory instruments (automotive, medical, aerospace), precision lighting (LEDs) and telecommunications (NAS 2013). Telecommunications dominate the current optoelectronics market, and optoelectronic transceivers are manufactured in the millions annually (Yole 2016). Transceiver devices use light to send and receive information and electronic components to convert information to and from light for transmission or procession. Transceivers must first have their components fabricated (using a process of material deposition and etching to achieve desired structure), and then each component must be assembled into the whole: thus, different transceiver designs affect the requirements for fabrication by changing component characteristics and also affect assembly work by changing how components must fit together.

Broadly, two of the central technological changes ongoing in optoelectronics are automation and consolidation: automation in our sample occurs mostly in assembly (fabrication is already highly automated) and consists of introducing machines to substitute for manual tasks. Consolidation involves the fabrication of formerly discrete components as single parts, thereby changing the content of fabrication and the structure and extent of assembly (Fuchs et al 2008).

Because optoelectronic devices combine electronic and photonic elements, they pose a number of challenges in design and fabrication which differ from traditional electronics. The materials used for optical components (lasers) are often not the traditional silicon of electronics: common materials such as Indium-Phosphide have differing crystalline structures from silicon which add complexity to the interactions between them and limit co-fabrication (NAS 2013). Differences in the behavior of photons and electrons also mean that traditional semiconductor design solutions are not always well-suited to optoelectronic applications: one technical expert in our study noted: "The problem is that electrons will more or less follow the path you want them to [in a device], and photons don't." Indeed, CAD and other computer design solutions are not readily transferrable from electronics to optoelectronics in many cases, and while there is an emerging industry space for commercial optoelectronic design software, all firms in our sample relied at least partially on proprietary software developed in-house to accommodate their design technologies. Despite these differences there are broad overlaps in fabrication, and many optoelectronic producers rely on fabrication equipment designed for electronics.

The firms in our sample vary significantly in their degree of vertical integration: qualitatively, we measure integration by the segments of the value chain in which a firm performs its primary activities.[3] These segments are product design, process design, component fabrication and assembly. The most integrated firms in our sample perform all four segments. Several firms in the sample are design-focused, specializing in the development of new transceiver designs, often with no fabrication capabilities: these are instead provided by foundries, which offer contract manufacturing services (often these same foundries serve the wider semiconductor industry as well).

5. Qualitative Findings: Embedded Knowledge and Worker Scope of Influence in Innovation

The differences between optoelectronics and electronic semiconductors give the industry two important characteristics. Firstly, a lack of industry-specialized education. Second, a higher degree of technical uncertainty concerning product design and process. These two characteristics are associated with the importance of worker experience, firm structure and ultimately the role of shop floor workers in innovation.

5.1 On the Job Training and the Role of Worker Experience

The optoelectronics industry is affected generally by a lack of specialized education: national entities such as the American Institute of Manufacturing Photonics (AIM-Photonics) seek to address a perceived lack of technical training for production workers, especially in fabrication: for now, the firms in our sample rely heavily on training on the job and worker experience to make up for traditional educational resources.[4] Interviewees from senior technical staff to supervisors who began as line workers

[3]It may be possible to think of a firm's position in the industry into terms of outsourcing rather than vertical integration. However, outsourcing assumes that a firm performs a segment of the value chain, outsources the next and then eventually re-integrates outsourced work into its own production sequence: many firms in our sample may be destinations for outsourcing rather than outsourcers themselves, and hence a focus on which segments of value-added a firm performs is more informative for our analysis.
[4]AIM-Photonics Technician certification program: https://aimphotonics.academy/workforce/workforce-training/technician-certification

consistently describe to us a premium in their hiring decisions on worker experience within the industry, frequently citing the lack of formal training or educational alternatives.

The majority of trained engineers, who usually come into optoelectronics from a more traditional electronics background, must undergo a significant degree of on-the-job learning not only about the firm's specific processes or designs, but also about the technical characteristics of optoelectronics. Multiple interviewees across different firms indicate that even PhD-level engineers usually do not come to the optoelectronics industry with full technical knowledge, and that adaptation could take a year or longer in some cases.

Shop floor workers perform tasks in the fabrication and assembly stages of value added, though they have potential roles in design. On the shop floor, our sample firms employ workers in consistent broad categories: operators, responsible for production tasks and interacting with or monitoring machines during production, technicians, responsible for setting up and calibrating machines (though some job-setup is typically performed by operators) and for intervening when machines fail and cannot be restored by operators, supervisors, responsible for organizing and often training operators (though training is sometimes performed by more experienced or "lead" operators), and equipment and process engineers, responsible for solving high level process issues (often but not always in dialogue with workers). Typically, an operator's role is fairly scheduled, performing well defined tasks throughout the shift, while technicians, supervisors and engineers often performed more ad-hoc functions. Our focus in this report is primarily on operators.

On the job training at all levels of employment is a feature in all manufacturing firms in our sample. Among shop floor operators, training is generally between two and eight weeks (with two the mode) for a given assembly task, while in fabrication training times are often much longer, sometimes lasting up to 6 months for a line worker to become qualified on a single type of fabrication equipment.

In both fabrication and assembly, training general begins with a manual outlining both equipment and (in the case of assembly) manual work procedures that the worker will perform, as well as general introductory training to the work environment. Optoelectronic components in both fabrication and assembly are highly sensitive to material contamination and damage from static discharge, and in addition to the motions of their primary work, shop floor employees must learn protocols to minimize the risk of foreign contaminants. While some procedures such as switching into static-deterring slippers to step onto an assembly line are relatively trivial, more exacting standards in sensitive clean-room environments require full cleanroom body suits (affectionately referred to as "bunny suits" by several engineers and lead operators in our sample). Workers must learn not only how to change in and out of the suits in a timely fashion,[5] but how to operate effectively within the constraints of the suit, which interviewees with cleanroom experience attested can be both a physical and a psychological challenge. Though all cleanroom employees receive demonstrations, instruction is not sufficient, and for fabrication workers especially,[6] learning how to operate in the cleanroom suit is one of the first markers of the cleanroom experience that several firms in our sample value highly in manufacturing employees.

The format of worker training after basic instruction is strongly associated in our sample with the scale of production at a plant. Workers typically receive active instruction on a piece of equipment, often from a more experienced worker or supervisor but, at the largest production scales, from trainers. In the transition from instruction to experience-building, depending on the scale of production, the equipment may on-line or off the production line. Whether from equipment off the production line or being used less efficiently by a less experienced worker, the cost of training in terms of "idle capital" is lower when work is principally manual (e.g. attaching an optical fiber): it may not be cost-effective for firms to dedicate high capacity, high-cost equipment to a small flow of trainees. However, at the largest scale of operations, some firms in our sample maintain internal training programs with full time training staff and training-purposed multi-step equipment and workstation layouts. These layouts can also be reconfigured to train workers for specific processes or to retrain workers for novel processes.

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[5] A senior engineer in our sample noted that he could do it in two minutes but knew of employees who could change in "about 30 or 45 seconds."

[6] Though some highly sensitive assembly steps may also be performed in a cleanroom.

Except for the largest training programs with worker testing protocols, the best indicator of successful training is successful work, embedding the measurement of a worker's skill in their direct job performance. Workers who begin to perform production activities on the line typically graduate from training to a probationary status (usually 3 months to a year and longer in fabrication than in assembly: see Table 1 for details) after demonstrating a certain number of proven good parts coming from their station. Probationary workers typically work under conditions with a greater ratio of supervisors to workers, or in smaller groups with a core of experienced workers. The involvement of supervisors or more experienced workers in the work of the trainee can be constructed through limitations on the tasks that the trainee or probationary worker is permitted to perform (such as calibrating a machine at the beginning of a shift), but it supervisor and senior worker involvement can also be at the discretion of more junior workers as they refer production problems up the managerial hierarchy.

Table 1 Education, Training and Experience of Optoelectronic Shop Floor Operators

Occupation	**Education**	**Training & Probation**[7]	**Average Experience**[8]
Assembly Operator	High School (Less in developing nations)	2-6 weeks training 3-6 months probation	1-3 Years
Fabrication Operator	High School or Technical Degree[9]	1-3 months training 3 months - 1 year probation	5-10 Years

Unlike in industries such as automotive assembly, where workers may be cross-trained across different equipment (Jordan, Inman and Blumenfeld 2004), optoelectronic shop floor operators tend to be dedicated to a specific type of equipment or (in the case of testing) class of equipment types. Equipment-specific expertise is narrower in fabrication, where a worker may be responsible for a single, specific

[7] Ranges expressed across firms and across steps within fabrication and assembly.
[8] Calculated from interviews and turnover rates across firms.
[9] Most fabrication operators in our sample were high-school educated, but all interviewees confirmed at least some fabrication operators on their shop floor with technical degrees.

machine and the jobs for which it is calibrated. Greater levels of qualification across the firms in our sample corresponded with greater worker autonomy: a fully qualified operator might be responsible for multiple machines, prepare them for jobs without technician support and serve as the first interrogator of equipment in the event of failure. Shop floor operators in optoelectronics are almost always at least high-school educated in the U.S. and developed world, sometimes less so in contexts such as developing East Asia. Assembly is usually a higher turnover environment than fabrication (and, hence, mean experience tends to be lower), but both have a wide variety of experience across workers, often less than five years in assembly but commonly up to ten or twenty years in both assembly and especially fabrication. Generally in our sample, an assembly operator's performance gains from experience plateau after two to three years (based on observations at four plants), while the greater variety and complexity of equipment in fabrication can extend the gains from experience over years – an operator in fabrication typically works more years before an internal promotion (e.g. to lead operator) than does an assembly operator. Experience can manifest as a higher rate of performance with fewer errors committed by a worker (as in the example of cleanroom suits), but it also appears in problem diagnosis and solving: for instance, an experienced operator can learn to visually identify inputs that are likely to cause production errors in a machine, or can learn to recognize and solve failure states that are not identified by the manufacturer or, indeed, result from nonstandard applications of equipment in a novel production process.

Internal promotion for operators based on experience and performance is common throughout our sample, though more so in fabrication than assembly. First, the classification of "lead" operator usually is used to reflect operators whose experience and skill make them suited to train others, but also to handle one or more complex pieces of equipment with greater autonomy and, often, to serve as a second line of problem-solving after less experienced workers. Many firms also have a strong pipeline from operators to technicians, waiving or reducing formal educational requirements for workers who develop expertise on specific machines: for U.S. workers, a promotion from operator to lead operator to technician means a shift in wages from about $14/hour for entry-level assembly workers to about $20/hour for more senior operators up to $28/hour for technicians, usually with a further premium for fabrication workers. This pipeline is especially important in firms that make use of custom or customized equipment, where outside training and certification are not useful measures of qualification.[10] Most direct hires in technician roles have at least a two-year degree, though in practice the workforces in each firm are about equally split internally between high school and technical degrees, reflecting a significant level of advancement through experience. Higher supervisory roles and even engineering positions can also be reached through experience in some firms, though formal education becomes a stricter requirement for engineering in all the cases we observe: equipment and process engineering teams in our sample features some cases of individuals with a two-year technical degree, but we observe no cases of engineering-level workers with only a high school degree. Moving from process to product engineering, we observe a mixture of bachelor and master level engineers: master's and doctoral-level engineers and material scientists are predominant in the firms we observed at the leading technological edge of the industry.

5.2 Technical Uncertainty and Firm Structure

The second industry characteristic, technical uncertainty, means both that production failures are frequent (and potentially quite expensive) and that the outcomes of design changes or new production processes in terms of productivity, skill requirements or labor demand are uncertain at the outset. From the firm perspective, the process of innovation begins with a change in product design (often to meet a specific client's need), which is performed by several design engineers of various specializations, from more general roles such as layout design (how components fit together into a system) and circuit simulation to component-specific work such as laser or waveguide design: their product is then passed to fabrication engineers, who judge the feasibility of production and then engage production workers (the same process is later repeated for assembly).

[10] Notably, however, more customized equipment sometimes means that some technician roles are subsumed to the equipment engineers who designed the equipment.

Production failures, investigation and rework or redesign are common at these stages: indeed, our firms reported at least one and often two iterations of experimentation and redesign stretching from operators back to design engineering roles: iterations might take a month, but often stretched for six months to a year, with full development cycles from initial design to full production on the order of two to three years for new material platforms and typically a year even for incremental product innovations. Several firms cite continued technical uncertainty until the first 100,000 units of a new platform have been shipped, sometimes a year or more after the beginning of production "ramp-up." All firms in our sample describe a learning experience in production with each new design, and as we will expand in the next subsection, a sometimes-central role for production workers.

The structure of firms in our sample is also associated with different levels of technical uncertainty, bearing out the innovation literature and also helping to inform how technical conditions and firm structure may interact to in turn affect the role of workers. Table 2 lays out the key organizational forms that occur in the industry and in our sample and maps these to the broad value chain described in section 4, and then to the level(s) of technical uncertainty faced by corresponding firms in our sample.

Broadly, there are three categories of firm models: transceiver manufacturers (fabless, meaning without fabrication capabilities in-house, or with in-house fabrication), which span product design and at least some production, contract manufacturers (foundries and contract assembly), and consultants and equipment manufacturers, which directly (consultants) or indirectly (equipment manufacturers) participate in design of product or process but not production. Transceiver manufacturers self-defined in our sample based on performing product design, which differentiates them from contract manufacturers (foundries and assembly). Equipment manufacturers implicitly set some of the conditions for process design, and in our sample also designed specific operational protocols for their machines, sometimes collaboratively with customers. In addition, though not a model for firm organization, the optoelectronics industry hosts the American Institute of Manufacturing Photonics (AIM-Photonics), which performs an industry-support role similar to a cutting-edge foundry or contract manufacturer for experimental product and process development (Manufacturing USA 2020): such manufacturing institutes suggest a possible public analogue to the firm structures and their implications discussed in this report.

Table 2 Technical Uncertainty and Firm Integration Along the Optoelectronics Value Chain

Organization Type(s)	Product Design	Process Design	Fabrication	Assembly	Technical Uncertainty	Number of Processes in Sample
Integrated Transceiver Manufacturers	Yes	Yes	Yes	Yes	Low (Legacy) to High	3
Fabless Transceiver Manufacturers	Yes	Yes*	No	Yes*	Low (Legacy) to High	2
Foundries	No	No**	Yes	No	Low	1
Contract Assembly	No	Yes	No	Yes	Low	4
Design Consultants	Yes***	Yes***	No	No	High	3
Equipment Manufacturers	No	Yes	No	No	Low to Medium	2

*Some firms observed performed limited outsourcing of process design and assembly functions but all kept at least a majority (by cost) of these activities in-house.
**The significant capital outlays for foundry equipment and relatively small capacity demanded by most foundry clients make it very rare for foundries to make any change in production process outside of the allowable process parameters established by the foundry's Process Design Kit (PDK). However, experimental work within the constraints of a PDK is often performed by a Foundry on behalf of a client.
***Design Consultant processes studied accommodated both process and product design, varying according to the client's needs.

The configuration of a firm's position along the optoelectronic value chain is associated in our sample with the level of technical uncertainty under which the firm may operate. Contract manufacturers need high volume processes that can be readily adapted to the needs of new customers, and thus tend (especially in the case of fabrication) to engage in production at low technical uncertainty. The exception to this role is the case of experimental services offered by these firms, usually providing small batch production to facilitate product design at a client firm: in these cases, however, the contract manufacturer can provide feedback but did not usually perform a technical design role (e.g. in the manner of a design consultant). All CMs must resolve some uncertainty concerning the adaptability of their standard production processes to new customer demands: the level of customization available to clients sets the level of technical uncertainty. Foundries have well-defined Process Design Kits (PDKs) which they offer their clients: documents or software which lay out the parameters under which the foundry's equipment and workers are rated to operate and which serve as a first constraint on the designs that customers may attempt to produce: assembly CMs are often more flexible, and thus take a more active role in process design, though even here the level of process and equipment customization is much lower than at transceiver manufacturers that assemble in-house.

Design consultants and equipment manufacturers may specialize in a specific set of processes or product characteristics, but their rule is usually to offer solutions to firms without in-house capabilities in certain parts of design. Thus, the design consultant and equipment manufacturers will often tend to serve smaller firms, potentially without the resources to fully integrate their production activities. Design consultants are not typically engaged in incremental work on existing platforms – more often, the processes we studied had to do with leading-edge designs and novel materials, such as highly consolidated devices (multiple components fabricated as one without assembly) or new material platforms to more easily co-fabricate components. These design consultants are nevertheless typically separate from shop-floor production, often performing design work and material science work away from the customer's facilities. Equipment manufacturers, in contrast, typically provide varying types of equipment for established functions – they are not usually developing equipment for entirely novel processes and designs, as these tend to be firm-specific and thus a narrow share of the industry and market.

Transceiver manufacturers, then, would appear to have the greatest range of value added activities in their sphere and thus the greatest tendency to produce under technical uncertainty. Indeed, many transceiver manufacturers choose to integrate certain production activities for finer control and a less constrained design space for their products. However, some of the industry's leading-edge firms in design are fabless, suggesting that a significant degree of innovation is possible without direct control over the entire value chain. Meanwhile, certain "legacy" designs, meaning products on well-established platforms with procedures and component designs relatively unchanged in the last fifteen years,[11] are produced by vertically integrated firms, following well-understood processes with little further innovation in design or process around the legacy product. Technical uncertainty is thus associated with but not fully married to the degree of integration: rather, the resources available to a firm in pursuing innovation differ according to its position on both dimensions.

In the following figure, we summarize our analysis to show how the organizational models of the optoelectronics industry map onto the dimensions of technical certain and firm vertical integration.

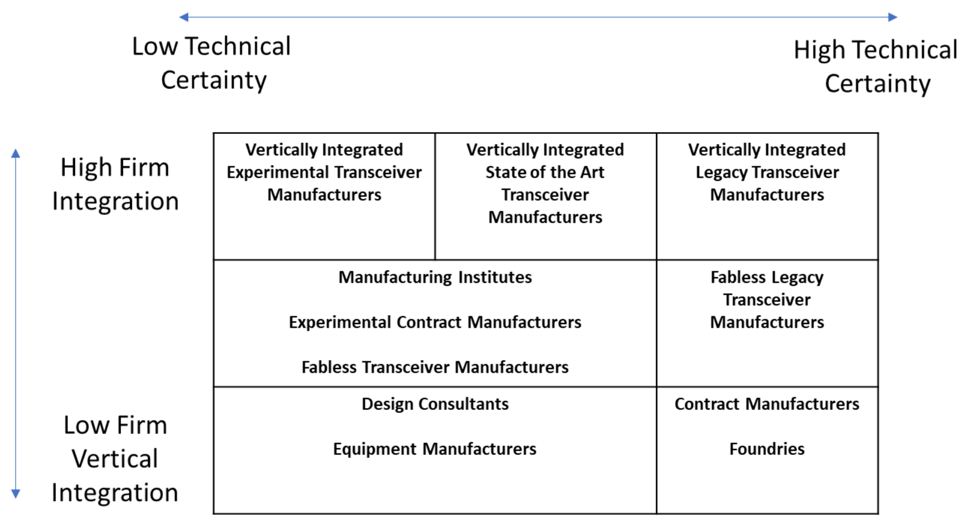

Figure 1 Distribution of Technical Certainty and Integration Across Organizational Models in Optoelectronics

5.2 Embedded Knowledge and Worker Interfaces with Technology Change

The fabrication of optoelectronic chips, laser diodes, waveguides and other components that make up optoelectronic transceivers involves a dozen or more unique pieces of equipment used in a process of

[11] Because many optical device applications have a standardized industry form factor and many device consumers put a premium on an established history of product reliability, legacy designs can survive for extended periods of time even against competition from new devices with the same form factor but different internal design.

hundreds of production steps. Some individual machines may be applicable in dozens of production steps but will be dedicated to just a handful of steps. In some cases, the reason is simply one of capacity – the relevant process steps demand sufficient equipment time that a machine can be fully dedicated without being underutilized, and keeping the machine calibrated for the same small set of steps saves time for engineers, technicians and operators. In assembly, we observed that it is common for workers to be dedicated to specific manual tasks: the number of employees hired for such tasks suggest that this dedication was possible because such tasks demanded enough person-hours to fully occupy a worker.

However, not all equipment dedication falls neatly into the logic of capacity: there are facilities with individual machines on a full production line for a mature design with a history of hundreds of thousands or millions of units running below capacity (we have captured some at half capacity or less) working on an often small subset of the steps in which they could be applied, while a different machine of the same type handles other steps: the scale of production does not explain such underutilization, and the dedication of equipment to steps would seem to rule out the use of duplicate equipment to take over during production failures and unscheduled downtime. Calibration time (that is, "transition costs" from one step to another) provide one explanation, but across multiple companies and fabrication sites, engineers have often described another reason: they simply do not know how to replicate the parameters under which a given piece of equipment operates economically. Under such conditions, a machine and its neighbor of identical manufacturer and model are nevertheless not interchangeable.

In optoelectronic fabrication, processes are "qualified" (similarly to workers within a process) after they reach certain standards of scale, uniformity of output and minimal rates of failure or unexpected downtime: often, however, equipment is also qualified for a given process. That is, the process is not universally qualified for use either with other equipment or under contract fabrication with a foundry:[12]

[12] While foundry customers can specify quality standards and perform their own quality control procedures, such as product sampling, and they can negotiate (usually on the basis of their product volume) for limited exceptions to the Foundry's PDK, they have relatively little direct control in the standard foundry model over which procedures and configurations the Foundry will accept.

the process meets standards when performed on the exact machines on a production line, often in an exact order. This idiosyncrasy of capital is the "sorcery" (among other colorful descriptions given by interviewees) mentioned by at least one engineer at every facility or firm we have visited.

To develop a reproducible process from these first black-box procedures on idiosyncratic equipment, some firms adopt an experimental line approach, using a dedicated production environment to test and develop new processes, often using the most experienced operators and giving them an active role in innovation. Another configuration of production with a similar function to the experimental line is the dedicated training line used by some firms: when adopting a new processes, especially in high process-turnover environments such as contract manufacturing, retraining may have an experimental role in the transmission from process design to practice, as experienced workers identify (and perhaps resolve) the flaws of a new process while learning it.

While idiosyncratic equipment is seemingly more common in experimental contexts in our sample (owing to technical uncertainty and lower reproducibility of working processes and equipment), it is a very real phenomenon even moving outside of the laboratory or experimental line and onto the fab floor. Something in the machine's history, its path to qualification, gives it the specific qualities to perform exactly the operations needed for a successful fabrication step and cannot easily be imported whole cloth to its neighbor. When fabs do gain the capability to replicate operations across equipment, they will often impose very strict design limitations for clients and in-house designers on what can be produced on the equipment: outside of those parameters, one engineer tells us, "they cannot guarantee a good part." These processes can be tamed, but often they remain poorly understood, and deviations can trip back over into the domain of "sorcery," where the quirks of nominally standardized equipment and the intuition of the machine operators become an indispensable part of production that is sometimes unaccountable by rationalized process management.

The uncertainty and specificity of such processes and equipment demand embedded knowledge, often not only of a process but of a specific piece of equipment. While a process remains uncertain and potentially difficult to reproduce, highly specialized, deeply contextual worker knowledge may be crucial to successful operations. This unique knowledge may also require worker skillsets that differ from those of workers within operations that are reproducible *de novo* outside of equipment history and calibration path-dependency. The practitioners of "sorcery" may be line workers as much as engineers.

Multiple firms that we interviewed note, unsurprisingly, that the degree of embedded knowledge was greatest with machine operators and technicians, then among process engineers (some of whom were involved in building custom equipment), then among design engineers. These differences widen considerably depending on the degree of vertical integration: the most highly integrated firms that we study report a close interface between development engineers and technicians or production workers, who often supply feedback on machines under development. In this manner, workers can have an active influence over the nature of their future work, by affecting the characteristics of future equipment, in which they will again develop specialist expertise. Here, the degree of customization plays an important part: when equipment is purchased from a general semiconductor or other industrial line, the role of the engineer in adapting it may be lower and the opportunity for the worker to engage in the development of future work reduced. Even firms that we interviewed with a focus on providing process solutions for manufacturers had an emphasis on designing a process in-house (with their own dedicated team of higher-skilled operators and technicians) and then teaching it to workers at a client firm, contrasted with the more dynamic interface between process development and worker that we observed in integrated firms.[13]

On the other hand, when a firm is disintegrated (as several in our sample are), the possibility for interfaces between workers and the firm's technological development is often reduced. Workers at contract manufacturers must work within carefully fixed parameters to meet promised specifications: in turn, the constraints on allowable operations in these disintegrated environments limit the design space for

[13] At a higher level, interactions between workers and process engineers will inform reworking of broader assembly processes and indeed changes in product architecture if fabrication or assembly prove unsuccessful in their initial state.

firms and constrain their technological development. Put otherwise, environments with greater roles for workers in innovation may also provide greater technical flexibility to designers.

In our firm sample, the embedded knowledge of workers becomes less sought after for innovation when considering manual production tasks. Manual work in optoelectronics includes the delicate art (so-described by a trainer) of attaching optical fibers at an angle and degree of precision that to-date has not been fully automatable in any context we observe. Not all workers possess the manual dexterity for such a task, and multiple firms noted the importance of experience and precision: yet such processes, while demanding, have much lower technical uncertainty than the "black box" of the fabrication environment. The skill and experience of the worker appears more disconnected from a role in innovation in our sample when the technical facts are well understood.

The implications of technological uncertainty for worker participation in innovation may also be connected to the scope of uncertainty. Consolidation and automation in optoelectronics are an illustrative case. Consolidation, as a large-scale design change, requires simultaneous outlays of capital to modify large segments of production from fabrication to assembly, and in turn the consequences of technical uncertainty can be far-reaching, affecting the entire production process (Combemale, Whitefoot, Ales and Fuchs 2020). Automation, in contrast, carries some technical uncertainty but is more local, as individual process steps can be automated, sometimes (though not always) independently of the rest of the production process. The difference in scope of uncertainty between the two technologies is reflected in the experimental lines used by some larger firms, primarily for testing the production of new designs rather than for equipment automation: whereas automation might be more easily offloaded to engineering or indeed outside firms, handling a specific sub-process, the broad technical uncertainty associated with consolidation means that capturing the effects of design change requires a working example of every production step affected. These experimental lines, especially in their lack of mass standardization of equipment and procedures, allow workers an active and potentially more autonomous role as participants in technical innovation.

6. Discussion:

We summarize and synthesize our findings concerning worker participation in innovation in the following figure. Note that the level of "integration" influences how far the production worker's presence on the value chain extends up toward product designers: the least integrated employer would only accept production orders from clients, with little to no customization or adaptation of process outside of a standard offering, thus allowing no context for a change in technology to be informed by the worker's embedded knowledge. At a high level of integration, the firm would operate from the shop floor to the product design room, with direct linkages at least between workers and process engineers if not up to the design stage. As we have seen in the case of manual labor in assembly compared with fabrication, the degree of technical certainty of the firm, more so than whether a task is manual or not, is associated in our sample with the degree of engagement of the worker in innovation: uncertainty was the recurring theme in contexts where firms engaged significantly with production workers as direct participants in the firm's technology development efforts.

Thus, we propose two axes associated with the level of worker participation in technological development: technical certainty and level of integration. In the next figure, we build on our analysis of the distribution of optoelectronic organization models to show how technical certainty and level of vertical integration are associated with worker participation in innovation. Both axes increase the degree of worker participation: more integration gives the worker potentially farther-reaching influence on development, while less technical certainty makes the worker's knowledge more urgent to avoid costly failures.

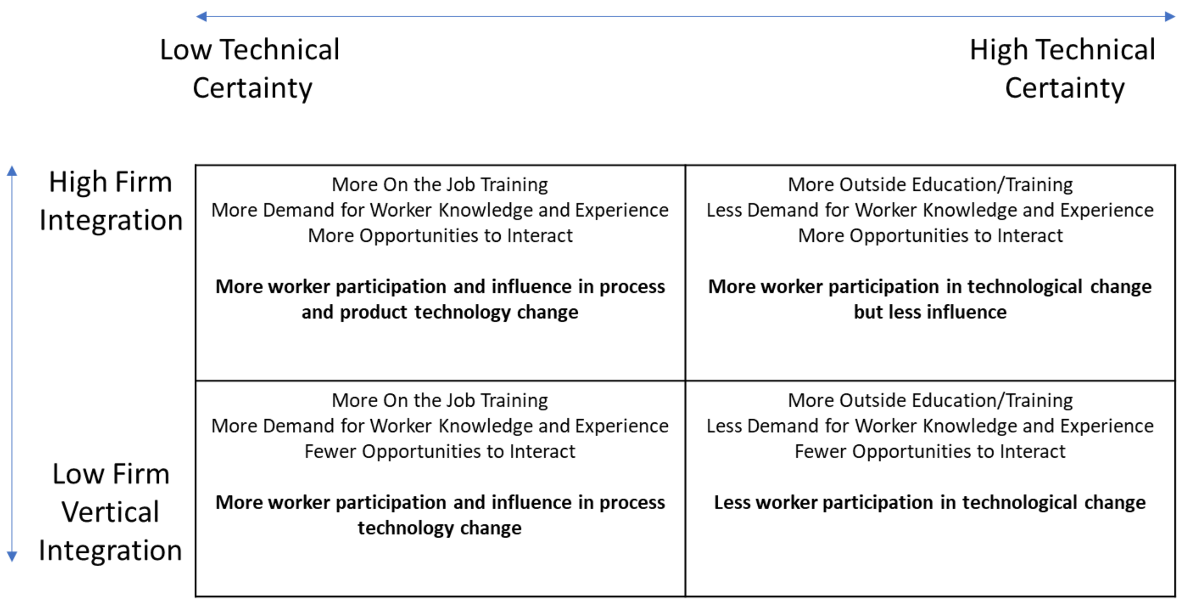

Figure 2 Worker Participation in Innovation by Level of Firm Value-Chain Integration and Technical Certainty

These findings are drawn from recurring themes in interviews with optoelectronics industry members at all levels of employment, and they are consistent in the U.S. and abroad, but further empirical work will be needed to separate these associations from other firm characteristics, and to collect the necessary outcome information to test them as mechanisms for worker participation. Further research is also needed to determine the extent to which participation as alternative to passiveness or conflict in worker experiences of technology indeed results in different employment, wage and psychological outcomes (e.g. a greater sense of ownership over a process of technological change which in current literature is associated with fear and frustration).

Optoelectronics has a high variety of vertical integration and technical certainty, but another important trait as noted in our analysis is its lack of formal educational resources, resulting in greater firm reliance on worker experience and on the job training. These traits are not universal in manufacturing, and we show in stylized form in Figure 3 how other industries may map onto dimensions of technical uncertainty and vertical integration. We also note a third dimension from our analysis, sector-specific technical education: this dimension is more helpful for inter-industrial comparison, as educational resources are generally limited across optoelectronics. In industries such as Aerospace and Automotive manufacturing, with less technical uncertainty than optoelectronics and greater technical educational resources in both secondary and tertiary education (Lloyd 1999; Lin, Chen and Chen 2008)), we would expect a reduced premium on worker experience and on the job training, and potentially reduced reliance in innovation on the localized "sorcery" of workers expert in the operation of specific equipment and uncertain processes.

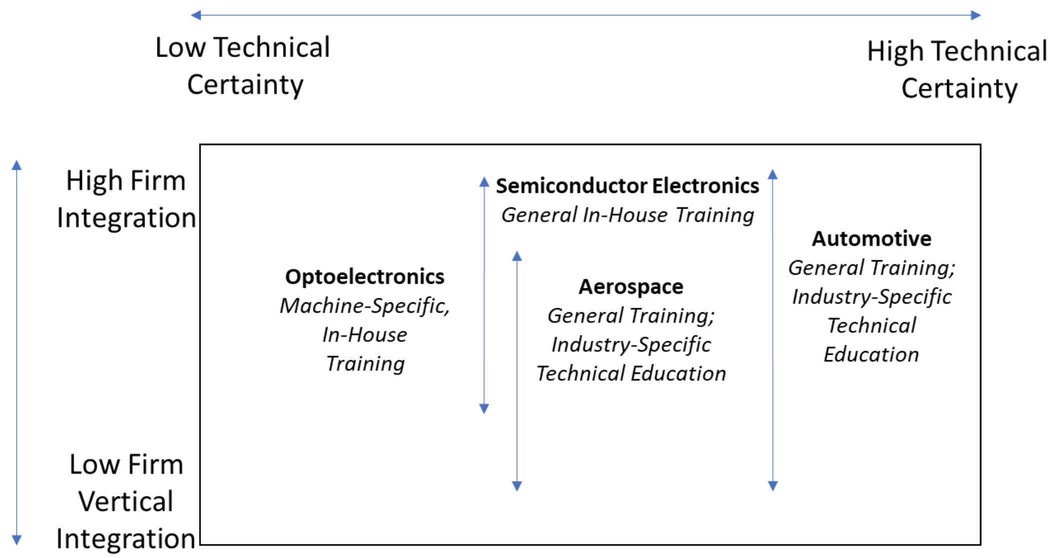

Figure 3 Stylized Industry Distributions by Range of Vertical Integration, Technical Certainty and Educational and Training Programs

With the association between the level of vertical integration, technical uncertainty and worker roles in innovation comes a possible new dimension for policy: policy mechanisms which encourage reshoring of production, firm integration or interfirm collaboration on technical issues also have implications for the part that workers will be enabled to play in the innovations that affect their work and the economy at large.

7. Conclusions

This report draws on extensive interviews with optoelectronics employees with experiences from the shop floor to product design and senior management, in order to study variations in the scope of worker participation in technological change. We find associations in our qualitative data between high levels of firm integration, high levels of technical uncertainty and the demand from firms for active worker participation as a contributor of knowledge and co-performer of innovative activity. Integration allows interfaces for worker knowledge to be adopted and uncertainty makes the worker's embedded knowledge a crucial counterpart to imperfect technical understanding in engineering. With the influence of technological change on worker feelings of employment insecurity in many contexts, it is important for labor policy to identify opportunities for workers to take on a more participatory role in technological change, and to recognize that policy implications for firm vertical integration and interfirm innovation collaboration may also have direct implications for the role of labor as participatory in innovation rather than only recipient of its consequences. An important insight of our findings is that firm characteristics could affect their incentives to engage workers as co-innovators, suggesting opportunities for a cooperative approach that can benefit workers and firms. Further research is needed to establish more clearly if the associations described in this report can be used to inform policy mechanisms, and indeed to evaluate empirically the benefits to workers of participation in the process of technological change.

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