Of chips and men: When working in Industry 4.0 is more human than expected

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In order to address the challenges of efficiency and manufacturing quality, the high levels of automation and data integration that characterize Industry 4.0 make it possible to produce customized runs at a similar cost to mass production, which leads to the creation of vibrant and complex work situations. In "flow" industries, such as microelectronics, very real human work becomes less visible as it only occurs in the event of a flow or process interruption. But what exactly are the consequences of this automation, pushed to its maximum, on the work and the skills required for production operators? This paper is based on an industrial case study, where the search for high performance levels and the increase in automation lead to increased monitoring of anomalies. The theoretical framework chosen is that of invisible work and its threefold experience (Gomez, 2013), which allows us to discover a change in work that is not really considered by the official organization. Thanks to a qualitative approach combining direct observation and semi-structured interviews, this research reveals that the work experience is marked by a ballooning objective dimension, a far cry from the most frequent, flattering presentations of Industry 4.0. A collective, non-official component is still necessary, with many interactions. Lastly, the subjective experience reveals many areas of tension. Thus, "4.0" work, even if it is more automated, turns out to be much more human than expected.

Introduction

> "A vision of the future in which we somehow take leave of material reality and glide about in a pure information economy" (Crawford, 2010, p. 9).

Smart factory, industry of the future, and digital business are some of the many terms used to refer to the concept of "Industry 4.0", an expression first coined in Germany in 2011. This industrial revolution, defined by the European Commission as "the end-to-end digitization of all physical assets and integration into digital ecosystems with value chain partners" (2020), is often compared to the revolution that took place in the 19th century given the rapid pace and scale of the transformation under way. Firms are in this respect expected to switch from mass automation to optimized automation, and from a digitalization of processes to advanced information technology (Gaudron, 2017).

For ten or so years, various publications dedicated to this field have – besides feeding the hype – attempted to give an insight into Industry 4.0 with regard to its actual dimensions and the many issues it raises. To be able to create customized runs at a similar cost to mass production runs, firms need to overcome a number of obstacles: combining top-down planning and analysis of reportable and multi-form data throughout the "automation pyramid" (BPI France, 2015); ensure the successful functioning of "end-to-end" processes so that the entire production chain has access to authoritative information in a homogeneous environment; and implement an adapted supply chain that departs from industrial mass production culture.

However, this does not mean that the essentially human-centric challenge of the transition to Industry 4.0 is of least concern. As demonstrated by Durand *et al*. (2014), this development in industrial information systems has resulted in a massive increase in management tasks, information overload, more stringent requirements and an erosion of interpersonal relationships. As has been observed in certain sectors such as aerospace, petrochemicals and nuclear power, complex work situations have emerged that can be deemed "dynamic-based" since they are beset by constant change, tasks with multiple focus areas, and work dynamics that alternate between routine and unforeseen events (Amalberti, 2001).

And yet, as Barcellini has noted (2019), these work situations continue to be generally given little consideration in relation to Industry 4.0, since human-centric factors are barely factored into this revolution. Galindo *et al*. (2019) recently stressed the difficulties of bringing the interests of stakeholders in this process into line; Compan, Cutarel, Brissaud, and Rix-Lièvre (2021) have begun to shed light on professional dilemmas, the cognitive and social facets of human-machine interaction, and an emerging insufficient capacity. However, empirical approaches relating to ongoing changes and their effects are lacking (Magone and Mazati, 2019); a forward-looking approach to Industry 4.0 on the labour and human resources front (Bootz *et al*., 2022) still needs to be further developed, and the state of knowledge remains patchy.

As a result, this paper seeks to help ensure improved human resource management within the context of Industry 4.0 by factoring in the actual work of the operators concerned. What consequences do automation pushed to its limit and digital integration have on human work and the production operator profession? Following an overview of the state of knowledge and the issue accompanied by a conceptual framework, we will present a case study conducted in the microelectronics sector. This case study will enable us to take on board the experiences of operators and the need for change in human resource management: the work of Industry 4.0, despite being more automated, has turned out to be much more human than expected.

Industry 4.0 as a process requires in-the-field investigation, particularly by examining work experiences

Industry 4.0 should be understood as a process rather than a fixed concept. While the available literature flags up some of the major challenges it poses for work organization, it also encourages a better understanding of work experiences to gain an insight into how the profession of production operators is changing.

Industry 4.0, a concept with many definitions

From the outset, it is not easy or quick to define Industry 4.0. Table 1 below lists some of the main definitions that have been proposed.

Based on these various sources, Industry 4.0 is not limited to the scope of plants, but covers the entire value chain in which it is incorporated. An ongoing process which is not set in stone, it creates, by means of automation and computerization implemented to the greatest extent possible, complex work environments combining a streamlined and fluidity-focused approach. Remote real-time access to multi-form data (production and control data) has resulted in a new form of human-machine interface. In this respect, we suggest including the following information in the definition of

Authors	Industry of the future
Brynjolfsson & McAfee (2014)	Fusion of the Internet and factories enabling multi-sectoral connection.
Themeco (2016)	Change in the organization of work, practices, capacities and relations creating opportunities for social transformation in working relations.
Lu (2017)	Interconnection and computerization in traditional industry, relating to the principles of interoperability, virtualization, decentralization, synchronization, modular design and a service-centric approach.
Dachs *et al.* (2019)	Components and machines communicate and co-ordinate their operations in factories and (global) value chains.
European Commission (2020)	The end-to-end digitization of all physical assets and integration into digital ecosystems with value chain partners.
Marnewick & Marnewick (2019)	Integration of various technologies, enabling ecosystems to operate smartly and independently, decentralize plants and incorporate products and services.
Couzineau-Zegwaard & Meier (2020)	Real-time access to all information in the value creation process, factoring in the needs of suppliers and customers through interface between humans and machines within a cyber-physical system.

Table 1: Some definitions for Industry 4.0.

Industry 4.0: Industry 4.0 is not a state but a process of real-time interface between various production systems, encouraging instant discussions and data exchanges, and as a result bolstering the human-machine-product three-way relationship.

Some major challenges of Industry 4.0 have been identified for work organization

In the 1980s, Boyer (1986) referred to a process of abstraction of implicit work, which in his opinion is the result of technological changes. These days we are witnessing an expansion of "immaterial and cognitive" work (Barcellini, 2019). Within this context the available literature points out three issues: a new distribution of labor triggering a demand for new skills; teams being replaced by cooperation networks; and heightened risk management.

Firstly, the transition to Industry 4.0, like any technological change (Coron & Gilbert, 2019), is not merely a change in processes or technical purpose: It introduces an overhaul of structures and shifts the workload between operator and machine, all under more open and interconnected organization. As Romero *et al*. (2016) posited, we are bearing witness to an exponential increase in human-machine interactions, requiring new physical and cognitive resources. This "extended automation", a term coined by Kohler & Weisz (2021), will naturally wipe out certain job roles, but is also dependent on new skills being developed: "The 4.0 worker must be able to interact with all of the company's lines of business, understand their challenges and constraints, and know how to work collectively to achieve continuous improvement and problem solving" (Kohler & Weisz, 2021, p. 19). In the view of Hecklau *et al*. (2016), the competencies required are therefore not of a purely technical (understanding new processes) and methodological (problem solving) nature, but also are personal and social in nature: the ability to adapt when working under pressure, communicate and cooperate.

Secondly, work groups deteriorate amid increasing automation and digitalization. Caroly (2016, p. 101) stresses that in work groups, "the rules of professions and work quality criteria are shared [...] on the basis of recognizing competencies, trust and discussions on values. The vitality of a group can be gauged by the extent to which such rules are reworked". These work groups need time to adopt and internalize new techniques, but unfortunately little time is provided for highly regulated and automated activities (Clot & Jouanneaux, 2002). To address these "dynamic and complex" situations (Clot, 2006), work cooperation social networks are taking the place of groups. According to Gibson and Earley (2007), these networks solve problems and resolve anomalies through accumulation (assembly of information), interaction (exchange of information), examination (negotiation of meaning) and accommodation (use of information in performance). The emerging architecture of organization breaks down from a value chain to a constellation of archipelagos, shifting from a pyramid to a rhizome (Kohler & Weisz, 2021).

Thirdly, risks, which have always been a part of the industrial sector, are not eliminated by the technological developments currently taking place but are in fact being managed more intensively. Admittedly the role of the production operator has certainly always been to handle risks through their ability to solve problems with "inaccurate and uncertain information" (Benkhanouche, 1996, p. 9). However, faced with these dynamic environments, operators have to contend with what Amalberti (2006) calls "a largely implicit continuum", and must ensure a more complicated trade-off between restrictions and cognitive resources. They have to exercise judgement, their inductive reasoning, as well as their ability to improvise (Negri & Vercellone, 2008). The etymology of "improvise" is to act outside the normal course of time, but time constraints loom large over automated activities. Galindo *et al.* (2019) and Bennis (2021) even refer to the concept of "ambidexterity", a requisite quality for operators who must harness existing skills while also exploring new ones.

Issue overview and conceptual framework: the changing face of the operator profession needs to be analyzed by examining work experiences

A new shift in labor distribution characterized by closer human-machine interaction, a deterioration of work groups, increased work in networks and greater cognition required to handle anomalies are all changes highlighted in this literature for their inevitable impact on those who play a central role in the workshop, namely operators. This section will examine how automation in Industry 4.0 and in particular the increasing need for anomaly monitoring is changing the profession of production operator.

For production operators, despite the array of assistive and predictive technologies available, the "industry of the future" is not spared from unforeseen events. As activities become increasingly complex, the sheer number of players and a "requirement for increasing precision" require more complex monitoring work. Taking the analysis conducted by Amalberti (2001), it can be said that there is a clash between two types of monitoring (the reason behind the compromise mechanism): one covering the conducting of the physical process and the other covering the application of cognitive abilities. Faced with optimization that is at times inflexible, operators are required to ensure a trade-off between the restrictions in this situation and their own cognitive abilities in order to keep "humans in the loop" (Amalberti, 1994, p. 77).

The conceptual framework chosen by us to closely observe and analyze the activities carried out by operators uses the definition of « métier » ("profession" in English) determined by Clot (2007): the combination of personal, interpersonal, transpersonal and impersonal elements. So that this definition can be operationalized to a greater extent in the field, we will use the analytical framework provided by Gomez (2013) which incorporates this definition. According to Gomez, economic shifts currently underway have pushed managers to increasingly focus less on the content of work, making it in a sense invisible in the information systems developed, resulting in a widening gulf between managers and operators. Industry 4.0 operators are affected by tensions caused by a multifaceted work experience, in which objective, collective and subjective dimensions intermingle. This section will examine the consequences of a high level of automation on the objective dimension of work, whether collective work experience is still necessary, and what will happen to the subjective dimension of work.

Case study: a microelectronics industry with increasing automation

The basis of this section is a case study on an industrial group using a two-step qualitative methodology, enabling us to observe the work of operators who are central to the production process.

Overview of industrial case study

The business is part of the semi-conductor market, a fiercely competitive sector for a small number of global leaders, and notably has a plant to which a major R&D center is attached. As a diversified supplier of integrated devices, the business manufactures chips – semi-conductors – using 300 mm silicon wafers. The plant floor space has an ISO 04 cleanliness level, contains ten workshops, and is divided into four departments containing one hundred or so pieces of equipment. With a matrix arrangement, the plant has a product layout servicing various sectors such as the automotive, telecommunications and aerospace industries. To meet customers' increasingly diversified demands, the industrial manufacturing processes have been progressively automated and enhanced with new digital tools over the past twenty years as shown in Figure 1. For example, the basic system used to select batches of wafers was first upgraded with a semi-automated system in the 2000s, and subsequently with automated transportation and batch loading, and then with a batch classification system. During the observation period, automation was in its fifth stage, which entails the use of a digital tool for monitoring assistance; management is even envisaging a sixth and final stage that would involve outsourcing specialized operators for monitoring anomalies, in a dedicated area located away from the cleanroom.

The semi-conductor manufacturing process is based on a series of successive stages known as operations. The main process involves exposing the resin-coated silicon surface to a laser source using photomasks (reticles). In doing this, additional layers can be built up, and the active areas of transistors can be created. The following stage is called metallization, which involves applying layers of aluminum or copper connections to link the transistors together. The manufacturing process can last several weeks and require up to 600 stages that are front-end (manufacture of components, production of transistors through doping) or back-end (finishing work on transistors, interconnections). About fifty photomasks are usually needed to make just one integrated circuit. The semiconductors are put in their packages at other industrial sites.

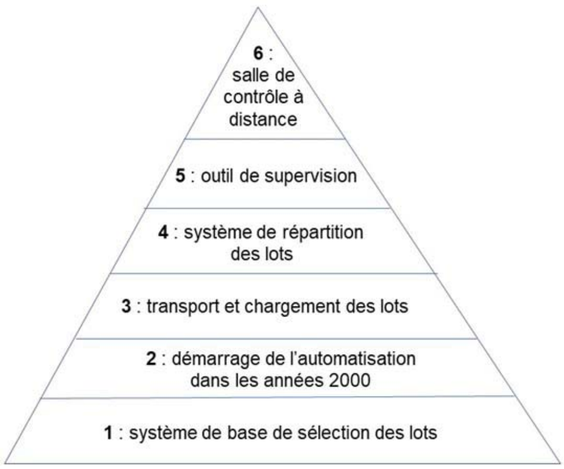

Figure 1: The automation pyramid within the plant.

FR	EN
6 : salle de contrôle à distance	6: remote control room
5 : outil de supervision	5: monitoring tool
4 : système de répartition des lots	4: batch classification
3 : transport et chargement des lots	3: batch transport and loading
2 : démarrage de l'automatisation dans les années 2000	2: uptake of automation in the 2000s
1 : système de base de sélection des lots	1: basic batch selection system

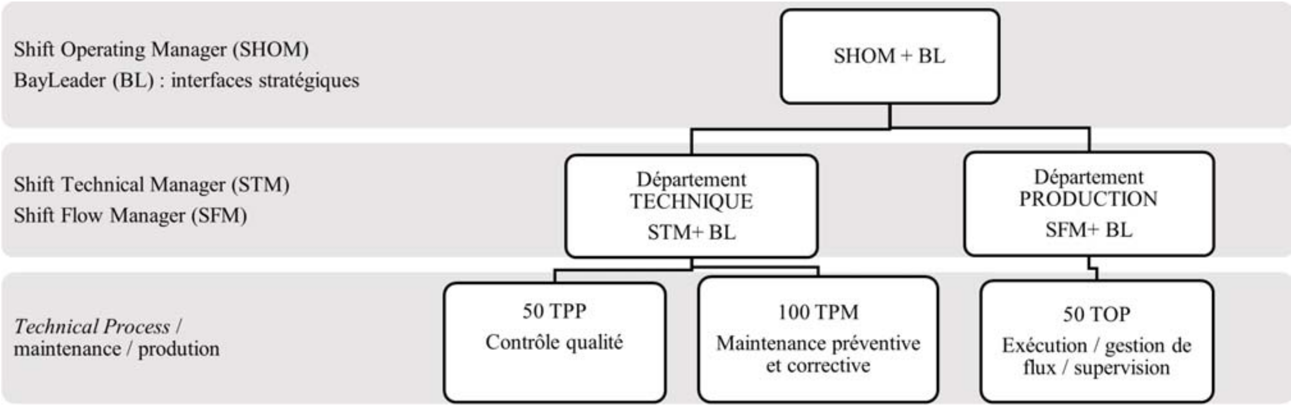

Figure 2: The plant's organizational chart.

FR	EN
Interfaces stratégiques	Strategic interfaces
Département TECHNIQUE	TECHNICAL department
Département PRODUCTION	PRODUCTION department
Contrôle qualité	Quality control
Maintenance préventive et corrective	Preventive and corrective maintenance
Exécution / gestion de flux / supervision	Implementation/flow management/ monitoring

Together with machines operating at maximum power, workers classified under three profession categories (manufacturing/maintenance/quality) – split into five teams working in shifts – manufacture nearly 75 million chips per month, seven days a week. Figure 2 shows the plant's organization chart. The "TOP" – the area of focus for this section – are, in the business's parlance, "production technicians/operators", responsible for implementation, management of flows and monitoring, but hereinafter they will be referred to as "operators".

A two-step qualitative methodology

The industrial site occasionally sustains productivity losses affecting batches and equipment, and the business's management has noted an increase in process times and a reduction in use time – which they deem to be "anomalies". However, the task of operators in the plant is precisely to ensure that the manufacturing process is productive, available and reliable. Therefore, performance is dependent on "the operator's ability to not interrupt the flow of whatever determines the financial flow" (Vatin & Rot, 2012, p. 2). In this respect, management wants to shift certain operators to overseeing anomalies and flow of processes in an attempt to improve the handling of malfunctions and unforeseen events.

This was the context in which we asked to conduct a study, which the business's management saw as an opportunity to gain more insight into the challenges and conditions of success behind this refocusing. We agreed that this study would not be action research, but rather collaborative research for which the cleanroom would be accessible to us provided we sent regular reports to management. We opted for a qualitative approach to understand the "why and how" of events by studying tangible situations (Wacheux, referenced by Dumez, 2021). We adopted the recommendation of Detchessahar (referenced by Journé, 2005) to opt for real-time observation that can help understand organizational and strategic aspects which are evident from hierarchical relationships, management tools and procedures, and also within teams.

Our on-site investigation took place between February and April 2021, and sought to examine the actual activities carried out by operators in the cleanroom, and to gather information on the work experiences of these operators in the wake of recent steps taken by the business to advance the Industry 4.0 process. It had two distinct stages: (i) from February to March 2021, non-participatory observation of 33 individuals from three teams working night and day shifts was conducted, and we carried out this work in the cleanroom; (ii) from March to April 2021, we conducted a series of 33 semi-structured interviews. The interview guide used covered the job descriptions, the work environment, interactions and relationships within teams, unforeseen events and the model operator profile, as well as the perceived benefits/risks of automation and remote work carried out by machines. We then transcribed and analyzed each and every observation, staying close to the central concept by recording comments to the letter, counting the number of frequency of observations, and classifying them by sub-topic (as per the analytic framework) or by adopting Gomez's segmentation approach. We supplemented these observations by examining in-house documents on the plant's industrial organization. Lastly, we had the opportunity to report the initial results both within our research team and to the plant's managers.

Operators at the heart of the production process

While an outside observer would expect the cleanroom to be a world stripped of human qualities populated primarily with robots, it is actually a bustling hive. While robots are installed on the ceiling, workers in coveralls wearing masks monitor the wafers every step of the way and work hurriedly together to ensure as many activations as possible. At first sight, it may seem that the work done in the cleanroom by these operators is invisible. With their work leaving little more than a shadow of a trace, the operators produce a product which cannot be seen, all the while using decision-making tools, in a hidden world away from the manufacturing processes.

The operators are tasked with ensuring that the manufacturing system is productive, available and reliable by overseeing the complex process set out above. The progress of the stages of the industrial process – cleaning the wafers, manufacturing the various layers, etching the circuits to name a few – can be easily disrupted by the smallest risk arising from interconnected production and monitoring systems: this is undoubtedly why in the job description, summarized in Table 2 below, there is a heavy stress on working in compliance with the systems and within the production constraints. For example, there is mention of "follow[ing] safety rules", "keep[ing] close to the procedure error rate", "only carry[ing] out manual operations on a piece of equipment with prior authorization", and "respect[ing] the recovery time".

The operators observed in the cleanroom have worked in the plant for several years and so have experienced the introduction of some of the automation stages. When asked, the operators voiced their reservations and a certain degree of resignation concerning the apparent benefits of this progressive automation and digitalization approach:

> "Algorithms are created for an ideal world..."; "When it comes to computing, you can't create things from random"; "[All of us] in the production department [are] surprised".

Overall assignment	Efficiently operate equipment to ensure the product can be delivered from a qualitative and quantitative standpoint.
Safety	Follow the rules in force, and report any potential risks.
Quality	Keep below the procedure error rate, detect and report batches at risk of exceeding constraints.
Monitoring	Adopt closer surveillance, oversee the entire area under your responsibility and monitor flow activity in your area.
Production management	Observe full automation rules, only carry out manual operations with prior authorization, schedule/oversee the batches throughout the production process based on instructions given.
Communication	Ensure instructions are given to the subsequent shift team, respect the recovery time, encourage constructive talks, and act within the organizational and reporting line processes.
Teamwork	Respect attendance rates and the working hours, and adhere to rules for requesting leave and the clean concept.
Ongoing improvement	Suggest improvements for tools, processes and the work environment. Suggestions must be substantiated, demonstrating the potential benefits thereof.

Table 2: Job description in summary form.

Interpretation and discussion: working in the Industry 4.0 era, an objective experience WITH collective and subjective DIMENSIONS

There are two major factors that are common to these operators: an almost obsessive pursuit of performance enhancement, and the relationship with time constraints which are highly present across the entire product manufacture cycle. This "sedentary race for activation" is the result of efforts to combat cognitive overload: the flow of information is considerable, there are a wide variety of tools available, and many orders can lead to the need to make decisions and compromises. In this respect, work experience is not purely objective, but also collective and subjective in nature; paradoxically, this work becomes all the more human-centric as automation increases, requiring a change in HR management practices for this group of individuals.

An objective experience that also has collective and subjective dimensions

The successive stages of automation and use of digital decision-making tools could suggest that the human workload is reduced and facilitated, as the operators can stay focused on their computers and need to discuss matters with others much less. However, analysis has in fact pointed to the contrary: we have observed a ballooning objective dimension of work, a collective work experience characterized by close interaction, and ultimately a subjective dimension distinguished by several points of tension and a pursuit of recognition.

A ballooning objective dimension of work

> "We're not kept in the loop, we don't exist to them, they treat us like robots".

This quote from an operator may seem dramatic, but it actually is fitting when considering the long list of factors relating to the objective dimension of this work. For a first, this work is conducted in a cleanroom, a space with a controlled environment so as to attain optimum levels of cleanliness, a necessity for manufacturing electronic components at micro scale. The temperature (21.5°C – +/-0.5°C throughout the year), humidity and air pressure are kept at a specific level and the air flow is continuously filtered. These work environments are classified using a scale of 1 to 9 (ISO 1 to ISO 9), and so audits that do not identify the business are conducted, activity tracking measures are implemented and rules of conduct are enforced.

When they first join, operators undergo onboarding and are given their specific instructions. They are responsible for at least twenty or so technical tools – namely equipment and tools for monitoring flows, constraints and anomalies – and for the new digital assistance interface for monitoring. Operators "take stock of the inventory" both in terms of productivity (with specific priorities set for them) and quality (with the identification of equipment that no longer works, or of batches that are blocked).

In addition to tools and their respective performance indicators, other factors demonstrate the objective dimension and its major significance in the operators' work. For example, their working environment is deemed "a world of its own", with the requirement for operators to wear a standard coverall helping to start discussions and keep them flowing, bringing down any social disparities:

> "It gets people talking; we're all on equal footing".

Operators consider themselves to be working for the engineers in the offices ("little helpers") to ensure that the set time frames are respected. This sentiment appears to be stronger among the day shift teams given the R&D engineers' presence on site at this time, while the night shift teams play catch up for any setbacks in activations that occurred during the day. The operators' activities are defined by three key factors: (i) their varied nature ("I never know whether it's going to be a relaxed or tricky day"); (ii)receiving instructions so that operators can "take stock of" the inventory from one shift team to another ("this points out the trends to us"); and (iii) the pressure of pursuing enhanced performance ("activation occurs every 30 minutes", "it's a sedentary race") – even on a voluntary basis to find meaning in work ("I'm going to seek out that little additional gain").

At the end of their shift, operators have to get ready to hand over and provide priority information to the next team. With the aid of technical tools, they report on past activity and "check out" by taking stock of the end-of-shift inventory. For them, it is a case of quickly closing off their activities that will be picked up by others.

A necessary collective work experience involving many interactions

Shadowing the teams during their shifts allowed us to note that, contrary to what may have been expected, there is a strong collective work experience in the plant. This is particularly the result of risk management, which operators believe accounts for two thirds of their workload:

> "The tools raise too many false alarms and change their minds every seven seconds"; "We solve one problem, and then another pops up which triggers another one".

The presence of risks in an over-automated production process may be surprising: the risks have in fact not disappeared but have increased in number and decreased in severity due to the complex nature of industrial processes, which cannot be fully controlled. These anomalies in the production process require human intervention: operators therefore need to carefully evaluate and select from a large amount of data aggregated by IT tools. This is why operators must cooperate with others to obtain and cross-reference information:

> "There's a contact person for every blocked batch"; "You have to get along with your colleagues"; "Ultimately, once you know how to connect with others you will have a handle on this job".

While the team members who have been at the plant longest recall group work that was once much simpler ("Before there was a collaborative effort made for substantial tasks"), this collective dimension does not reflect smooth and evident collaboration:

> “We get by with what we have”; “I don’t know how many contact people we have”; “Each person protects their own interests”.

There is therefore no work group, but rather smaller groups that are formed or reformed and deemed scalable (*i.e.* of variable size), created with a view to acquiring useful information.

This collective work experience, required to manage risks, is formed from a web of necessary interactions between operators. Although “everyone does their own job”, “you need to get along with your colleagues”, “you need to identify information at all levels”, and, “you depend on the other workshop”.

A subjective experience with many areas of tension

Faced with an encroaching objective dimension in their work, as well as the need to rely on one another, operators have a subjective experience of their work that is mixed to say the least. On the one hand this is a good thing – when asked to describe their activities, operators for example found pleasure in their work thanks to the human interaction involved, the intellectual stimulation, the learning opportunities and the variety of shift tasks. A more unexpected finding was that they mentioned that inherent and primarily personal competencies such as interpersonal and social skills, meticulousness and an inquisitive nature are required to carry out their work.

However, the subjective experience of these operators working in Industry 4.0 is also negative. Faced with increasing automation, operators bemoan their reliance on tools (“We are now dependent, we are no longer worth anything”) and on equipment (“When a machine breaks down, it really breaks down”). In their view, the progress made in the Industry 4.0 organization process is not necessarily always encouraging news, since specifically human qualities are lacking:

> “We have lost knowledge with employee turnover”.

While automation does – and is acknowledged to – reduce the arduous nature of the work, the cognitive overload caused by machines has been singled out:

> “The mental workload is huge; the work piles up and we can’t handle it”.

In this respect, operators talked about their dilemmas when faced with orders that could easily be considered paradoxical: ensuring quality but also productivity, staying alert while also rushing to complete as many activations as possible, following the set procedure but also having to intervene. As one technician put it:

> “They don’t want to make a choice; they want to be able to do everything”.

Managing these areas of tensions could be eased by management officially recognizing them, but this is rarely the case: as an illustration, management believes that risk management only constitutes 10 to 15% of operator workload. The subjective work experience for operators is therefore defined by this push for recognition:

> “We are always fighting to get more information, and all the time we have to explain the problems faced, justify ourselves and draft reports. Nobody is aware of the workload”; “Managers have a rigid perspective, [...] in the production department we see things in real time”.

Work becomes increasingly complex and human-centric as automation ramps up

As mentioned earlier, given the current state of knowledge of Industry 4.0, one of the clear findings made was that this technological development had the unique quality of exponentially increasing the number of human-machine interactions that require not only technical skills but also methodological and social ones. Our analysis of the work experience of operators in the case study corroborates this finding, demonstrating that human-machine interface forms part of their interactions. Their profession particularly requires interpersonal skills, and they need more social qualities to succeed at work. An inquisitive nature, strong social skills and a competitive streak also emerge as required competencies and personality traits.

However, the plant under examination has revealed three factors that have been overlooked in research available thus far and even more so in corporate presentations on the “industry of the future”:

- The first factor is that the high level of automation and computerization has not necessarily made work in the plant easier or more flexible: automation and the introduction of an IT interface for monitoring have made decision-making more complex, and the physical toil has been replaced with cognitive overload. IT interfaces made possible with technological progress are definitely a “tool to be used tentatively”, but also add another layer of abstraction.
- The second new factor revealed by the case study is that the collective dimension of work has not been eliminated: while there is no longer a general and stable work group in the workshop, there are still many interactions between individuals that represent ad-hoc groups. When interacting with others in person or remotely, operators are able to consolidate and cross-reference information that is sometimes based on potentially different interpretations; in time and with experience, they learn who to contact and, after many exchanges, to tell the difference between real and false anomalies.
- The third factor is the most important in our view: the fact that the required evaluations and human-made decisions have become more difficult since, according to operators, they do not receive the recognition they require. The operators talked of a “fatigue to report”, a “serpent eating its own tail” and a “wasted effort”: “it ushers in a lax attitude, and breeds contempt”. This subjective perception of a lack of recognition is certainly a point of attention for management, which is preparing for the next and final stage in automation – the establishment of a remote control room. This project entails setting up a remote operation center (ROC) and relocating operators from the cleanroom so that they can specialize in tracking anomalies using a new computerized assistance tool for

monitoring based on huge quantities of data. This new frontier of Industry 4.0 will allow for, in the words of a manager, “streamlining, a departure from the routine” and optimized monitoring activity, so that productivity losses resulting from anomalies can be minimized. However, at the time of our study, only a small minority of operators support this new step in Industry 4.0, with many concerned that the individuals involved will be isolated from others and cut off from people with whom they must stay in contact in order to carry out all the necessary evaluations and decisions:

> “We need to know the contact people, otherwise we have no connections”; “If we are away from the site, we are of no use”.

A change in HR management is required for these operators

In this case study, the HR department is rarely or never called upon by the cleanroom’s management to contribute to its discussions on the organization of Industry 4.0 manufacturing; this is undoubtedly the result of an engineer culture that is first and foremost focused on technology and a particular perception that HR managers primarily focus on social relations. Nevertheless, changes in the HR management practices for operators would be welcomed following on from the analysis of the work experience that we conducted, particularly to support the establishment of the future remote control room. We believe that two specific changes are crucial.

The first change we recommend relates to recognizing the work for what it truly is. As it stands, operators believe that their activity is inadequately and unfairly assessed:

> “Managers don’t understand the profession and yet they’re the ones rating me? HR recruits new staff [but] they also don’t have a clue about the job”.

We noted a significant discrepancy between management’s perception of risk management and that of the operators: a useful first step would be to officially recognize this discrepancy and work to construct a shared perception of risk management, along the lines of Perrenoud’s suggestions (2019). Perrenoud posits that managing unexpected events is part of any high-level skill. Another approach to achieve recognition that we suggest is to work on the required and employed skills of operators, using the terms coined by Retour (2005). The job description for operators, summarized above, details the mandated work and lists the expected skills that mainly relate to the observance of engineering rules. However, after shadowing workers, we noted many skills that were used but not required according to the job description, such as the ability to identify the right contact person and to evaluate and select several information sources in real time. If the HR department launched a project to elucidate the skills actually used, not only could the job description be updated but also the problem of the operators’ lack of visibility – a concern for many of them – would be avoided.

> “We’re given too little consideration”.

The project could lead to an expansion in assessment criteria, compared to the current situation in which the assessment of operators continues to be focused solely on the number of wafers manufactured and compliance with the process.

A potential second change that we suggest is to expand and foster spaces for dialogue. The concept of spaces for dialogue, based on the fundamental work of Clot (2015) and Detchessahar (2013) is increasingly considered a practical solution to psycho-social risks; this mechanism was mentioned in the Lachmann, Larose & Pénicaut report in 2010 and then explicitly called for in the National Multi-Sector Agreement of 19 June 2013. In the cleanroom, the many interactions observed between operators, required to diagnose risks, are in fact micro-spaces for dialogue. However, in this case, these spaces are reserved for the operators. Discussions on job performance are therefore incomplete:

> “The people in the field feel like they are not being acknowledged, that others are deciding what to do with the cleanroom without asking for their opinion”.

We suggest using the onboarding period as an opportunity to consolidate and expand these spaces for dialogue with the superior.

Conclusion

In a pursuit for increased performance, heightened by the global boom in the semi-conductor market, the business examined in our case study, which started the Industry 4.0 process quite some time ago, is about to embark on a new stage involving the outsourcing of anomaly control. Shadowing in the cleanroom allowed us to shed light on the little-known reality of Industry 4.0 work: a ballooning objective dimension in which cognitive overload supplants physical toil; a collective dimension that is still necessary but scarcely acknowledged, and; subjective work experience with several areas of tension and a desire for recognition. Working in Industry 4.0 is undoubtedly more human than expected: far from replacing humans with machines, it reconfigures humans’ relationship with equipment and calls into question individual and collective ways of working.

There were limitations to this research project: the case study focused on the perspective of operators, but the views of other stakeholders such as on-site management should also be taken into account. Our observation period also took place during a large-scale change i.e. the establishment of the new control room, which could call some of our current conclusions into question. Because of this, we are planning to continue our research to observe the implementation of this new work situation, to identify the defining characteristics of the new monitoring activity, and understand its repercussions on actual work and on the skills used.

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