‘The Discipline of Steel’: Technical Knowledge in the Coordinative Practices of Steelmaking

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Accepted: 5 January 2024

Abstract. This is a study of the cooperative work of making steel in a contemporary steel plant. The study is, first of all, a study of the coordinative practices of a cooperative ensemble of operators controlling a time-critical transformation process, while spatially dispersed at different work stations across the plant, working under quite different and varying local constraints and requirements, with only rudimentary means of ongoing communication. Their individual and local contributions to the overall effort must be minutely synchronized to meet the strict temporal requirements of the operation as a whole. These challenges notwithstanding, the operators manage to act concertedly to produce quality steel and to do so routinely. The question is, how do they manage to do that? As the workers in the setting generally are not able to coordinate their cooperative effort discursively, it is analytically both feasible and necessary to foreground and identify the knowledge of metallurgy of steel and of the plant that enables them, as they go about their own local activities, to apprehend the problems and intentions of their colleagues as reflected in the changing state of the technical processes. The underlying thesis of the study is that in order to answer the general question of how workers engaged in cooperative work are able to heed the activities of their colleagues, and to do so routinely, we are well advised to ‘take the concept of practice seriously’.

Keywords: Coordinative practices, Concept of practice, Mutual awareness, Technical knowledge, Skilled perception, Infrastructures, Process control, Steel production, Ethnography, CSCW

1 Introduction

‘But in their rage, the gods forgot the secret of steel, and left it on the battlefield. We, who found it, are just men: not gods, not giants, just men. And the secret of steel has always carried with it a mystery. You must learn its riddle, Conan, you must learn its discipline.’

Conan’s father to young Conan (In Conan the Barbarian, 1982)

1 Movie manuscript by John Milius and Oliver Stone, 1981.
This article is a study of the cooperative work of making steel in a contemporary steel plant. As such, it is a study of one of the critical industries of modern civilization.

Iron is remarkable for its affinity for forming alloys of the most diverse kinds. The most important of these are the carbon alloys of iron. These range from the ‘raw iron’ produced by blast furnaces (a.k.a. ‘pig iron’ or ‘cast iron’), which is rich in carbon (up to 6% C), to pure iron or ‘wrought iron’, which is very low in carbon. What is called ‘steel’ is the family of carbon alloys of iron in the narrow band from about 0.03% C to about 2% C. Steel nevertheless exhibits an astounding variety of properties. At one end of the spectrum, steel can be extremely hard and even brittle, while it, at the other end, can be ductile and malleable, susceptible to bending, drawing, and rolling; it can have very high tensile strength or it can be elastic. Some steels are robustly shock resistant, while others will snap under slight impact. Some steels are susceptible to fatigue, whereas others remain strong even when subjected to continuous vibrations or repeated deformations for years. Some steels can be welded, others cannot; some can be hardened and tempered, others cannot; some are amenable to machining, others are not. Some steels become brittle at low temperatures, where others perform well. Some steels exhibit remarkable resistance to corrosion, while others are prone to rust. And so on.

Steel is today produced on an industrial scale by processes of melting, alloying, and casting, and, moreover, by processes that can be rigorously controlled within known confidence intervals, because steel technology is based upon scientific metallurgy which, in turn, has firm foundations in solid-state physics and thermodynamics.

The impact of the development of scientific steel technology has been astounding. In 1850, before the advent of the technologies of contemporary steelmaking, less than 100,000 tons of steel were produced globally, which is significantly less than the 800,000 t steel produced annually by the small steel plant featuring in this study. By 1900, however, global production of steel had reached 28 Mt, surpassing the production of cast iron, and it then rose rapidly: 66 Mt in 1910, 190 Mt in 1950, and in 2018 more than 1,800 Mt, a growth rate of 6,000% over a century. This dramatic technical achievement has allowed steel to become ubiquitous. In per capita terms, steel output rose by orders of magnitude, from 75 g per year in 1850, to 20 kg per year in 1900 and to about 230 kg per year by 2010. It is the material of our railroads and pipelines, trains and ships, cars and bicycles, office towers and bridges, machines and tools, surgical instruments and prosthetic limbs, kitchen sinks and refrigerators (and, lest we forget, the materials of guns, cannons, tanks, and aircraft carriers). It is everywhere in our lives and workplaces. (Plöckinger and Eiterich 1985; Cullen et al. 2012; Smil 2016; Worldsteel 2018a, 2019).

Behind the remarkable growth in total output is a perhaps even more impressive growth in the productivity of steelmaking. With the ‘open-hearth’ (or Siemens-Martin) furnace, which was the dominant steelmaking technology from the
1860s to the 1970s and thus for most of the twentieth century, the time to produce 300 t steel from raw iron was about 9 hours; however, the ‘basic oxygen furnace’ (BOF) technology that was developed in the course of the last half of the twentieth century, made it possible to reduce the time to produce the same 300 t steel from 9 hours to 35 min. At the same time labor productivity rose by three orders of magnitude, from 3 person-hours/t in 1920 to 10 person-seconds/t in 1999. However, the BOF technology has significant drawbacks. Most importantly, it cannot handle charges with more than 30% of scrap iron and steel, which is an obvious disadvantage in a world where the stock of steel has been steadily accumulating. After concrete, steel is now the most prevalent material on the planet among the ‘anthropogenic materials’ and it offers an enormous and steadily increasing reservoir of inexpensive ferrous materials that are readily available for recycling. Consequently, the share of BOF technology in global steel production is being overtaken by the ‘electric arc furnace’ (EAF) technology, which today accounts for almost a third of the global production of crude steel. EAF technology is comparable to BOF in terms of ‘tap-to-tap’ lapse time, but is vastly more flexible in terms of input and output and again vastly more productive in terms of capital cost per ton. (Jones et al. 1998, p. 525; Smil 2016, pp. 45, 101–105, 184; Worldsteel 2019).

This is the context of the work setting described in this study. Steelmaking is a critical industry, and it is high tech. In view of the economic and social importance of such work, however, the work of making steel has received remarkably little scholarly interest. The present study is a humble contribution to balancing that deficit.

More specifically, however, the present study focuses on the coordinative practices that underlie these stupendous advances.

1.1 The research question

The study is, first and foremost, a study of the coordinative practices of a distributed ensemble of cooperating operators, spatially dispersed at different work stations across the plant, working under quite different and varying local constraints and requirements, and with only rudimentary means of ongoing communication. In fact, the coordination of their distributed activities is accomplished, to a large extent, devoid of their having recourse to visual monitoring of colleagues’ conduct and without much talk or other forms of interruption. Not only that; they are dealing with a time-critical transformation process: the process cannot be halted or reversed (without forbidding costs). Consequently, while fighting what seems like an incessant onslaught of contingencies, their individual and local contributions to

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2 According to the Worldsteel Association, ‘Recycling accounts for significant energy and raw material savings’. Recycling 1 ton of steel scrap saves the emission of 1.5 t of CO₂ and the use of 1.4 t iron ore, 740 kg coal, and 120 kg limestone (Worldsteel 2018b).
the overall effort must be minutely synchronized to meet the strict temporal requirements of the operation as a whole. These contradictory challenges notwithstanding, they manage to act concertedly to produce quality steel and to do so routinely.

The question is, how do they manage to do that? **How do the steelworkers manage to coordinate and integrate their distributed activities?**

Let me elaborate. The aim of the research is not to produce some general account of the ‘accomplishment’ of ‘social order’ (let alone, to proclaim yet another grand sociological theory). The aim is straightforward and mundane: it is to contribute to CSCW. Or more specifically, the aim is to contribute to the central CSCW research program, initially outlined by Lucy Suchman (1987), which is devoted to the issue of incorporating ‘plans’ in computational artifacts ‘as resources for situated action’. As expressed in an early, very tentative, formulation, a CSCW system, like any other computer system, ‘is based on a model of an aspect of the world’; in the case of CSCW, ‘a model of a social world’. For users to be ‘in full control’, ‘the system should make the underlying model accessible to users and, indeed, support users in interpreting the model, evaluate its rationale and implications’ (Schmidt 1991a, pp. 9 f., 13). This in turn raised the issue of how to identify and express the pertinent features of ‘a social world’ so as to construct such a model and make it accessible. As the problem was later expressed, the model of the coordinative protocol ‘must be perspicuous, i.e., accessible and intelligible to actors **at the semantic level of articulation work**’. Accordingly, ‘the objects and functional primitives available to actors for defining or specifying the protocol must be expressed in terms of categories of articulation work such as roles, actors, tasks, activities, conceptual structures, resources, and so on that are meaningful to the participants involved in terms of their everyday work activities.’ Moreover, the computational artifact must be ‘constructed in such a way that its stipulations can be related to and expressed in terms of the objects and processes of the field of work’, i.e., in domain-specific terms (Schmidt and Simone 1996, § 22, p. 186). In sum, incorporating models of coordinative protocols in computational artifacts, and that in such a way that actors remain supported by the artifacts when dealing with contingencies (variations, anomalies, breakdowns), requires that **the categories in which actors orient to, express, and reflect on their cooperative work activities and their coordination are identified and, eventually, expressed in computational objects.**

There is nothing extravagant or farfetched in this program. It is bread-and-butter design work in interactive computing. As opposed to, for example, a payroll program, which proceeds ‘**automatically**’, step by step, until it reaches its predefined end-state, the defining characteristic of the interactive computing paradigm is that

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3 The initial exploration of the notion of computational models of coordinative protocols as resources for situated action was carried out in the context of CoTech Working Group 4, funded by the EU’s Esprit Basic Research program, 1990–93. The contribution of Liam Bannon, John Bowers, Mike Robinson and the other members of WG4, as well as guest discussants, is gratefully acknowledged.
The computational artifact is designed to be highly reactive to the user’s every ‘command’ (e.g., deleting a word by selecting it and pressing ‘backspace’) and thus to be integrated into our practices in an entirely different sense, more intimately, as it were (Suchman 1987). It is therefore a central challenge to the design of computational artifacts to identify a lexicon of elemental categories of the practice in question (for a discussion, cf. Schmidt 2015b; Schmidt and Bansler 2016). This applies even more so to collaborative technologies and underpins each and every computational artifact that in some way mediate, facilitate, or regulate cooperative activities. For instance, a computational group calendar meant to enable people to arrange events (issue, accept, and decline meeting invitations, receive notifications of upcoming events, etc.) will incorporate a model of the calendrical protocol (expressed in object classes representing categories such as ‘date’, ‘time’, ‘duration’, ‘location’, ‘time zone’, ‘topic’, ‘host’, ‘invitee’, etc.).4

Now, the issue of determining such categories and incorporating them in computational models is manageable in so far as we are dealing with coordinative practices that rely on protocols (e.g., calendars and time measurement in the planning of events) that have already been developed by practitioners and analysts, and perhaps long since stabilized and even institutionalized (‘precomputed’, to use a term suggested by Ed Hutchins 1995, Chapter 3). However, the issue becomes a very challenging research problem indeed, as soon as we are dealing with coordinative practices that do not (to a significant extent) involve and rely on such already well-described and stabilized protocols, but rather are enmeshed with and form an integral aspect of actors’ taking heed of the ongoing material processes (and the concomitant bodily conduct of other members of the ensemble with respect to those processes). Initially dubbed ‘mutual awareness’, such coordinative practices pose a crucial research problem for CSCW, and it is not least because of this that ethnographic studies of work underwent a surge and came to play a critical role in CSCW (Schmidt 2000a). It is a CSCW research problem of the first order.

And here we are, back at the questions at hand: How do the steelworkers, dispersed over different stations of the plant, manage to accomplish continuous casting of quality steel at a high production rate and with an insignificant failure rate? And in particular, in which categories do they orient to, express, and reflect on their cooperative work activities and their coordination?

That is, the aim of this study is not to give a general account of the emergence of social order. It is not a contribution to the ‘ontology’ of the social sciences or any other branch of its metaphysics. The aimed-for generalization is not sociological but technological. The aim is, at one level, to provide a study

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4 The commonly used standard protocol is named ‘Internet calendaring and scheduling core object specification (iCalendar)’ and was initially specified in RFC 2445 in November 1998 (https://www.rfc-editor.org/rfc/rfc2445) and was later superseded by RFC 5545 in September 2009 (https://www.rfc-editor.org/rfc/rfc5545). For an account of the development of the iCalendar protocol, see https://icalendar.org.
of coordinative practices at a particular contemporary steel plant, focused on exploring how steelmakers employ their general metallurgical knowledge and their intimate knowledge of the idiosyncrasies of the plant to determine the unfolding state of affairs and stay on top of and ahead of events. It is a contribution to the to the CSCW corpus of studies of cooperative work practices. But at another level, the aim is to explore and, if at all successful, demonstrate how CSCW research can make headway with respect to investigating the categories in terms of which workers in their coordinative practices orient to the work of their colleagues in domains where coordinative practices have not, to any significant extent, been precipitated as specialized practices employing distinct precomputed protocols (e.g., incorporated in coordinative artifacts) but where the coordinative practices, in the main, are inseparably enmeshed with the control of the transformation processes. In short, in addition to contributing an ethnographic study of contemporary steelmaking to the CSCW corpus of workplace studies, the study is at the same time intended to contribute to the methodology of CSCW.

1.2 The ‘mutual awareness’ conundrum

‘The greatest miracle of all is that the true, the genuine miracles, can, and should come to, seem so commonplace to us.’

Gotthold Lessing: *Nathan the Wise* (1779)

The field work was undertaken at the Danish Steel Works Ltd. (Det Danske Stålvalseværk A/S or DDS) in Frederiksværk, Denmark. DDS converted iron and steel scrap into quality steel, in the form of plates for shipbuilding, boilers, and construction; in the form of merchant bars for structural steel; and, to a minor extent, in the form of carbon steel and special steel products. At DDS, the fieldwork focused on the Steel Plant where the initial processes of melting, refining, alloying, and casting take place. The subsequent processes of adjusting, cutting, normalizing rolling, etc. were not investigated. The main part of the fieldwork

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5 ‘Der Wunder höchstes ist, Daß uns die wahren, echten Wunder so Alltäglich werden können, werden sollen.’ (Lessing 1779). — Alfred Schütz quoted this clause by Lessing as an epigram when he in 1958 launched yet another assault on the problem of the ‘life-world’: ‘the idealities of “and-so-forth” and “I can do it again.” […] Hence: Its familiarity; pre-interpretedness; our power to act upon it’ (‘First notebook’, Seelisberg, Switzerland, 12–16 August 1958, in Schütz and Luckmann 1989, pp. 191 ff.).

6 Owned jointly by the A.P Moller–Maersk Corporation and the Danish state, DDS was allowed to go bankrupt in 2002, at a time when the rapid build-up of steel production capacity in China momentarily had reduced global steel prices dramatically. The Steel Plant structures were subsequently demolished and are now nowhere to be seen. The subtly concerted cooperative operation reported in this study is, therefore, a thing of the past. In spite of that, in what could easily be seen as a state of profound denial on my part, the account is written in the present tense.
was carried out, in intervals, from February 1997 to June 1998. After this relatively intense period, occasional field visits continued until March 2000.\footnote{The field research, its conditions and methods, are described in ‘Appendix I: The study’.}

The subsequent history of the study has been one of troubles. A first outline of the findings was drafted concurrently with the ongoing field work. However, because of relentless difficulties with developing an adequate analytic account of my findings and of its conceptual implications (and in part also due to life’s exigencies), I soon had to put the work aside. The writing was resumed in 2004, however, and resulted, in 2006, in a manuscript in which the descriptive analysis of my observations was fairly complete, while the conceptualization of the findings still amounted to little more than a bunch of fragmentary attempts. As I expressed it to a friend in the spring of 2005, I was stuck because I ‘lacked the language’ to give an adequate account of my findings. As it turned out, however, my inadequacy was not simply linguistic; it was conceptual, as will be clear in the next few pages.

I initially tried to account for my findings in terms of ‘mutual awareness’ (Schmidt 1998; Schmidt and Simone 2000). This term and its synonyms (e.g., ‘peripheral awareness’) had by then emerged as accepted shorthand expressions for the common observation that workers align and mesh their ongoing local activities with those of their colleagues and do so in an effortless manner (e.g., Gaver 1991; Beaudouin-Lafon and Karsenty 1992; Dourish and Bly 1992; Gaver et al. 1992; Benford et al. 1994; Schmidt 1997; Gaver et al. 1995; Gutwin and Greenberg 1995). The insistence in CSCW of the inexorability of this recurring observation, manifested in naming it ‘mutual awareness’, marked a break with the fundamental assumption in cognitive psychology that the human mind is a single-channel ‘information processor’.\footnote{The single-channel myth was, for example, expressed in a CSCW keynote lecture stating that ‘It is impossible to get information in or out of our head without paying attention. Yet attention, as Herbert Simon has noted, is a limited resource’ (Thorngate 2000). But as had then already been demonstrated by one of the founders of cognitive psychology, Ulrich Neisser, ‘there is no physiologically or mathematically established limit on how much information we can pick up’ (Neisser 1976, p. 99). It is simply a matter of acquired skills: ‘Practiced subjects can do what seems impossible to the novice as well as to the theorist […]’. The more skilled the perceiver, the more he can perceive’ (pp. 92 f.). (For a discussion of this myth, cf. Schmidt 2002b, §§ 3.2 and 7.2.).}

However, I soon found the very notion of ‘awareness’ in its various permutations inadequate. First of all, I had long found it problematic that CSCW studies of coordinative practices exhibited a strong predilection for focusing on ‘small groups’ or ‘teams’ or ‘focused collaboration’ defined by ‘face-to-face interaction’, i.e., discourse carried by speech, gestures, bodily postures (Bannon and Schmidt 1989; Schmidt and Bannon 1992; Schmidt 1994). That predilection is rarely, if ever, examined; nevertheless, privileged status is anyway implicitly granted to coordinative practices under conditions of co-presence, actual or emulated. The upshot is that the analysis of how workers align and integrate their individual activities with
those of their colleagues tends to be conceived of in terms of discursive conduct, while the role of the technical infrastructure (‘the field of work’) and workers’ technical knowledge is relegated to the background. As a result, the notion of ‘mutual awareness’ had become one of a presumably generic faculty on par with peripheral vision, abstracted from and independent of workers’ domain-specific and hence also historically specific technical knowledge and skills. My observations of the coordinative practices at the Steel Plant soon corroborated my misgivings and eventually made it clear that the notion of ‘mutual awareness’ cuts no ice.

By implying that the observed effortless coordination is a manifestation of some generic cognitive faculty, it was also implied that the deployment of these putative generic faculties were somehow categorically distinct from the wide range of historically specific coordinative techniques such as having project planning meetings, engaging in ad hoc chats around the water cooler or coffee machine, issuing formal commands, consulting clinical protocols and standard operating procedures, checking timetables and master schedules. What had been dubbed ‘mutual awareness’ was, I reckoned, rather to be conceived of as features of a complex of coordinative practices and complementary techniques (Schmidt 2000b; Schmidt and Simone 2000). It also began to dawn on me that the competencies underlying what was referred to by the term ‘mutual awareness’ were not a distinct type of practice on par with other coordinative practices but were logically primary to those practices, in that the latter presume that actors have the requisite capabilities (‘knowing how’) to heed relevant occurrences in the setting. This whole complex obviously needed unpacking.

As I began to be aware of my troubles, I first (beginning in 1998) tried to find conceptual grounding in Alfred Schütz’s notion of ‘meaning’, that is, his thesis that to a worker in the ‘natural attitude’ of everyday work the objects in the setting typically have unreflective ‘meaning’ to him or her: ‘the outer world is not experienced as an arrangement of individual unique objects, dispersed in space and time, but as”mountains,” “trees,” “animals,” “fellow-men”’ (Schütz 1953, pp. 7 f.). Thus, ‘we experience the world from the outset not as a “blooming, buzzing confusion” of sensory data, […] but in its structurization according to types and typical relations of types’ (Schütz 1959, p. 285). I initially found this take quite promising, but I just as soon began to realize that the phenomenological account was caught up in contradictions by virtue of its fundamental (and inescapably subjectivist) position according to which that ‘meaning’ is constituted by an essentially private ‘frame of interpretation’ (Schütz 1932, p. 57) that is projected onto an immediately meaningless perceptual flow, and, stemming from that, that ‘intersubjective’ knowledge is precariously produced by interpretive work in ‘face-to-face’ situations: ‘it is only from the face-to-face relationship, from the common lived experience of the world in the We, that the intersubjective world can be constituted’ (Schütz 1932, pp. 171). The notion that the ‘intersubjective world’ is constituted by a ‘We-experience’ of the ‘face-to-face-relationship’ and that the gap from subjective to communal is supposedly bridged by interpretive work falls on the rather trivial logico-grammatical observation that
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interpretive work in ‘face-to-face’ interaction already *presumes language* and social order *tout court* and that it right there enters an infinite loop with no off ramp.*9*

As I sensed (around 2000) that the phenomenological notion of ‘meaning’ was something of a dead-end concept, at least for my purposes, I tried to find complementary grounding in James Gibson’s (*obverse*) notion of ‘meaning’ as ‘information’ emitted by the environment (1979), by which I had only jumped out of the frying pan into the fire. In short, when the field work had been completed, I had landed in a doubly contradictory position (clearly visible in Schmidt 2002a).*10*

Finally, gathering that my position was untenable, I undertook what turned out to be a lengthy journey. As a first step, I realized that ‘mutual awareness is not a mental state that arises through some kind of osmosis, as a result of simply “being there”. It does not even make sense to conceive of mutual awareness as a mental state that anticipates or explains praxis. It *is* a praxis, or better: a *skillful praxis*’ (Schmidt 2000b). But shifting from a phenomenological to a practice-oriented terminology did not do any effective work. Nor was the unpacking done by appropriating and applying the family of ideas that was then being marketed under the brand name ‘practice theory’, for this approach (perhaps due to its roots in structuralism) reduced practice to mere regular behavior, sometimes ‘explained’ by reference to hypothetical and unaccountable entities such as ‘schemes’, ‘habitus’, ‘unconscious rules’, etc., and as a result ‘practice theory’ provided no operational path to giving rigorous accounts of practitioners’ skilled conduct. I therefore found it necessary (for me) to undertake a series of critical conceptual studies, drawing heavily on the work of Ludwig Wittgenstein (1937–44, 1945–46, 1949–51) and Ryle (1949, 1979), of notions such as ‘situated action’ (Schmidt 2011, Chapter 12); ‘tacit knowledge’ (Schmidt 2012a); ‘shared understanding’ and its cognates such as ‘shared goal’, ‘shared situation awareness’, or ‘shared intentionality’ (Schmidt 2012b, 2016); and, eventually, the concepts of ‘practice’ and ‘technique’ (Schmidt 2014, 2015a, 2018a, b).

The gist of all this is that the key to give an adequate account of coordinative practices — the coordinative protocols and artifacts as well as coordinative practices enmeshed with doing the work and doing it mindfully and heedfully — is to investigate the role of actors’ domain-specific technical knowledge and skills. The first step to unpack the methodological implications of this was taken in my introduction to the special issue of the *CSCW Journal* on ‘Awareness in CSCW’ (Schmidt 2002a), in a list of research questions that focused on the

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9 These issues obviously also gave Schütz pause for thought and doubt — as shown by his repeated but unpersuasive attempts to bridge the conceptual gap between ‘the face-to-face relationship’ and ‘the intersubjective world’. — For making me aware of the equivocality of my initial (1998–2002) position, I am indebted to Meredith Williams’s critical discussion of Schütz (1999, Chapter 2). (On the issue of ‘interpretive work’, see Schmidt 2011, pp. 380–387).

10 For a helpful critical discussion of Gibson, see Wes Sharrock and Jeff Coulter’s critique (1998) and the protracted and incisive debate initiated by it.
domain-specific categories in terms of which actors orient to, express, and reflect on their coordinative concerns and thereby transcended the contradictory position otherwise expressed in that article:

(i) Upon which evidence does an actor rely when heeding the activities of others? What data (signals, cues) are available to the actor? What is the actor able to perceive of the actions of others? […]

(ii) By virtue of which competencies are cooperating actors able to make sense of what others are doing? Which ‘taken-for-granted knowledge’ is invoked by the actor in making sense of the evidence available to him or her? Which “indicators” or “typifications” do actors primarily rely on? What do they monitor for and what is ignored?

(iii) How do actors exploit the material and conventional environment in monitoring unfolding events? Which indicators play a key role in determining the state of affairs? What is the relationship between the materiality of artifacts and their representational role as vehicles of signs?

(iv) How does the actor determine what is relevant to his or her own effort? How does the actor manage to sort out and pick up what is relevant? How does an actor, in modulating his or her activities so as to make relevant aspects thereof accessible to colleagues, determine what is relevant for the others?’ (Schmidt 2002a, pp. 294 f.).

These research questions indicated an operational path beyond empirically unwieldy notions such as ‘meaning’ and ‘affordance’ and instead pointed to actors’ organization of perception, their scanning strategies, the development of the technical knowledge underpinning the organization of perception and scanning, and the actors’ acquisition of that technical knowledge.

In sum, by focusing on the domain-specific categories of the technical knowledge in which actors orient to, express, and reflect on their coordinative concerns, the research questions outlined in 2002 indicated a path to understanding the effortless manner in which cooperating workers generally manage to coordinate their distributed activities, often without any discourse. Accordingly, when I revisited the issue of ‘mutual awareness’ many years later, in 2016, I concluded that we, instead of pursuing the elusive idea of developing a general conception of ‘mutual awareness’ by finding ‘commonalities across practices’, should realize that no general conception of ‘mutual awareness’ was forthcoming and that the analytic task rather was that of ‘analyzing the work practices in their rich complexity’ (Schmidt 2016, pp. 348 f.).

1.3 Methodological prelude: taking the concept of ‘practice’ seriously

In order to understand how the steelmakers routinely manage to act concertedly in producing quality steel, we have to move beyond merely, or primarily, relying on what might be termed a phenomenological reduction of ethnography to little more than participant observation laced with fragments of conversation. We need to take into account the technical knowledge underpinning
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the practices under study; that is, the specific relationship between, on the one hand, the technologies as a body of systematic knowledge or ‘theory’, and, on the other, the application of that knowledge in the midst of unfolding events, surrounded by the sound and fury of the melting, purging, refining, alloying, transporting, and casting of steel: in contingent action, ‘in the wild’, ‘when the rubber meets the road’, ‘in practice’. The study thus addresses, directly and squarely, the central tenet of CSCW, namely, the crucial and complex issue of the relationship between ‘theory and practice’, between ‘plans and situation action’. The underlying thesis of the study is that in order to answer the general question of how workers engaged in cooperative work are able to heed the activities of their colleagues, and do so routinely, we must, as suggested by Wynn (1991), take the concept of practice seriously.

Now, the concept of ‘practice’ was not the analytic frame for the field work but became an issue as it turned out that its clarification was a prerequisite for providing an adequate account of the observations (as developed in Schmidt 2011, 2014, 2015a, 2018a, b) and developed into the warp and weft of the analysis. Thus, instead of an exposition from first principles or similar propositions derived from a body of theory, the following analysis should rather be seen as an exposition of findings from which the author learned to use the concept of ‘practice’ to provide some order and in which it thus came to serve in a heuristic capacity. Be that as it may, a few summary remarks on the concept of ‘practice’ may help the reader keeping his or her bearings during the twist and turns of the account.11

The point of departure is that the concept-pair ‘theory and practice’ was developed (in Europe) in the late Middle Ages and early Modern Era so as to be able to reflect on and discuss the relationship between a body of technical knowledge (e.g., medicine, engineering, geometry, gunnery) and its application in action (e.g., treating patients, building fortifications, erecting cathedrals, preparing gunpowder and calculating cannon charges). This relationship had become particularly problematic with the increased use of writing in the conveyance of technical knowledge and especially with the development of science-based technologies and, by virtue of that, with the separation — in time, space, and division of labor — of the functions of planning and situated action, of conception and execution, and, yes, using terms introduced by the ancient Greeks for quite different purposes, of ‘theory’ and ‘practice’: ‘the Modern concept of “practice” conceives of action as guided by a “theory” in some strong sense’

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11 Or as a gesture of respect to the protocol of academic writing. — A reader, eager to get to where the action is, may want skip this section and the next, and jump directly to the field observations (Sect. 2 ff.), to eventually return to Sects. 1.3 and 1.4 in the context of reading the concluding sections.
The point of the concept of ‘practice’ was to be able to address, reflect on, and discuss the didactic and technical issues that arise when the creation and formulation of technical knowledge on the one hand and its employment in action on the other are separated in time and space, in a system of division of labor, and when technical knowledge therefore typically is expressed and transferred in writing (text, tables, diagrams, drawings, formulae). As succinctly summarized by Immanuel Kant half a millennium after the Modern Era concept of ‘practice’ was initially coined:

‘One calls a conceptualization of rules, even of practical rules, a theory when these rules, as principles, are thought of in a certain generality and thus have been abstracted from a multitude of conditions that nonetheless necessarily influence their application. On the other hand, one does not call any operation [Hantierung] a praxis; rather, only that effectuation of an aim is considered a praxis that is taken to be attained by following certain generally accepted principles of procedure.’ (Kant 1793, p. 127).

When describing a particular activity as an instance of a specific practice, we are conceiving of this activity in a particular way, namely, with respect to certain rules, principles, or norms pertaining to its performance that are upheld by practitioners, such as, for instance, criteria of what constitute doing the same, criteria of what counts as relevant, criteria of appropriate enactment and satisfactory outcome, criteria of adequate competence and proper comportment. That is, when we talk about a practice, we are engaged in the kind of discourse Ludwig Wittgenstein explored in his watershed analysis of ‘rule-following’ (1937–44, esp. Part VI and VII; 1945–46, esp. §§ 185-202); we are talking about conduct that is not merely a regular occurrence, a repeated pattern according to some scheme, but a conduct for which it makes sense to deem it correctly or incorrectly performed, ‘a consensus of action: a consensus of doing the same thing, reacting in the same way’ (Wittgenstein 1939, p. 184). We are talking about normatively committed activities, for which the commitment typically is established in a prior didactic setting, through instruction and training, as a result of which mastery is acquired and accredited. However, when talking about a practice, we are

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12 Wittgenstein used the term ‘commitment’ frequently in this context in the early 1930s, while he was exploring the notion of practice, both in his Cambridge Lectures in November–December 1930 (Wittgenstein 1930–32, 1930–33) and in his dictations to Friedrich Waismann (Wittgenstein, 1932–35, ‘Notebook I’). He dropped the term from his lexicon later in the 1930s, but it seems to me quite useful anyway. (For excellent discussions of ‘rule-following’ in Wittgenstein, see Minar 1986; Medina 2002; Williams 2010). (For a related critical discussion of the notion of ‘rules’ in ‘practice theory’, see Schmidt, 2018b).
talking about normatively committed activities with a view to their contingent performance, that is, the regularity in action as accomplished under the (in principle) endless diversity of particular circumstances, in the face of (in principle) a multitude of possible conditions, routine variations, unforeseen hurdles, breakdowns, from which the expression of the rules and principles are abstracted. We are, in short, talking about normatively committed but contingent activities.

Thus, when we talk about a practice, we are not merely referring to a pattern of behavior, a certain way of doing certain things. We are talking about a pattern of behavior in which actors not only exhibit regularity in their conduct but also (supposedly) are committed to do so.

Now, as often happens when a concept that has been developed to deal with a specific set of issues turns out to be quite useful, it is suggested that it may also be useful if its scope is extended by loosening some constraints, that is, in a secondary sense. Thus, the concept of ‘practice’, initially devised and used in explicit reference to a, typically, systematically expounded set of rules expressed in writing, a ‘theory’, has been found useful in anthropology and sociology, as a way to deal with regular behavior for which no such systematic ‘theory’ can be identified but to which the notion of normative commitment nonetheless applies in so far as practitioners can be observed to accept instructions given orally on how to proceed in a line of work, or agree on what is considered acting correctly or doing the same, or explain their reasons for what they do and how they do it by way of justification, or consent to corrections and modify their conduct. However, the noun ‘practice’ is also used (not least in sociological literature) in the loose sense of a pattern of behavior, without even implicit reference to some set of general principles to which actors are or can be (sensibly) held to account. Again, no harm is done in doing so as long as one keeps in mind that this usage leaves undetermined the crucial issue of what is the criterion of ‘sameness’ by which a particular activity is taken to be an instance of the putative pattern. If that is left undetermined, however, the concept of ‘practice’ has no analytic power; it has become mere jargon. For our purposes, for the purpose of identifying

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13 It is here relevant to note that the concept of ‘technology’ has been subjected to a similar extension of scope. Originally devised and introduced in the late eighteenth century as a label (on the model of names of disciplines like ‘zoology’) for systematic accounts of existing techniques in handicrafts and manufactories (Beckmann 1777) for the purpose of informing the same practices, it was later used for technical knowledge that ab initio is based on the application of scientific knowledge, as a shorthand for systematic technical knowledge. But at the same time its scope has been expanded to also denote technical knowledge simpliciter, of whatever epistemic status, whether systematical or not. By smothering the distinction between ‘technology’ in the sense of techniques (as in preparing a soft-boiled egg) and ‘technology’ in the sense of scientific technical knowledge (as in the chemistry of the formation of protein chains), the extended use may deprive us of the ability to differentiate when such is due. (The application of the term ‘technology’ for technical artifacts, however, is a barbaric category mistake of the first order: an electronic device is no more digital technology than sulfuric acid is chemical technology or a steel slab metallurgical technology). (Schmidt 2011, Chapter 11).
the categories in which actors orient to, express, and reflect on their cooperative work activities and their coordination, the criteria of sameness must necessarily be those applied by the actors. And indeed, the issue of doing the same is a vital practical issue for practitioners, and it is an issue they deal with routinely every day. Thus, if we, as observers and analysts, are to understand the specifics of the coordinative activities to be supported by computational artifacts, we first of all have to understand how practitioners themselves determine what is considered part of that practice and what is not (Schmidt 2018b).

We can only talk of ‘practice’ (without engaging in idle talk, that is) when the notion of correct or incorrect conduct, according to some criterion, applies. That is, the concept of ‘practice’ is of a different category from the notion of ‘tacit knowledge’ as initially propounded by Michael Polanyi (e.g., 1958, 1966) or as subsequently used in the quest for a general account of the emergence of social order as represented by, e.g., Pierre Bourdieu’s notion of ‘habitus’ (1972, 1980) or Anthony Giddens’s notion of ‘structuration’ (1979); or in the attempts by, e.g., Theodore Schatzki (1996) and Davide Nicolini (2012) to postulate a ‘practice theory’. What unites these positions is that they, in addressing orderly conduct such as skilled practices, reduce practices to manifestations of unaccountable constructs such as ‘hidden rules’, ‘unconscious rules’, ‘schemes’, ‘routines’, etc. This move is predicated on two logical blunders. First, it hinges on conflating the notion of ‘rule’ with that of the ‘expression’ of a rule. Thus, since observers often are unable to elicit a (to them) satisfactory rule formulation from the subject, then surely no such rule exists, or so the reasoning goes; and vice versa, since there often are rule formulations, in organizational handbooks, say, of which operators are unaware or indifferent, the conclusion is obvious: rules have no feet to stand on. The mistake lies in assuming that the field worker or some other observer has privileged access to determine what the rule may be or not be, while the rule, in fact, is internal to the practice and is determined in practitioners’ actual conduct and their mutual holding each other to account: rules are manifested in the regularities that are observably upheld in practice when referring to procedures, offering approvals or accepting sanctions, saying ‘oops’ or ‘sorry’, and so forth (Bittner 1965). Second, the mistake is thus predicated on the presumption that the criteria for determining what constitutes a practice are independent of the practice in question, whereas they — of course! — are internal to that same

14 The explanatory move of invoking ‘tacit knowledge’ or its cognates to account for practical knowledge has been widely influential, as is visible in movements such as science and technology studies (e.g., Watson-Verran and Turnbull 1995; Collins 2001, 2010), studies of artisanal work (e.g., Turnbull 2000; Smith 2004; Ingold 2013; Smith 2022), or ‘knowledge management’ (e.g., Cook and Brown 1999; Orlikowski 2002). It is far beyond the scope of this article to engage in a discussion of this scheme. I must here restrict myself to cite my discussions of ‘tacit knowledge’ and ‘practice theory’ (Schmidt 2012a, 2018b).
practice: the criteria of knowing how to do the same and of going on in the same way. This is how we ordinarily use the verb ‘to know’, as shown in the analysis of the concept of ‘knowledge’ in the writings of Wittgenstein (1945–46), Ryle (1946, 1949), and White (1982). By saying, ‘A knows x’, we’re not ascribing a psychological attribute; we are rather granting ‘A’ a specific kind of authority, namely, that of having a certifiable competence, according to some specifiable criteria: to give correct information, obtain satisfactory solutions to problems, perform some activity adequately, etc. Notions like ‘tacit knowledge’ and its next of kin, ‘bodily knowledge’, etc., may seem deep but they trade in tampering with the categories of our language. The result of all this is a mystification of practical knowledge (Schmidt 2012a, 2018b).

Closely related to the notion of ‘theory and practice’ is the concept of ‘technique’ in that a practice will always, in practice, rely on a repertoire of technical complements. A particular practice will, at a particular time and place, be characterized by a historically given repertoire of techniques (tools, materials, procedures), the configuration of which will be contingent, depending on tradition, local availability and cost of materials, the vicissitudes of knowledge diffusion, etc. as well as an element of serendipity. In fact, it is a defining characteristic of mastering a practice that practitioners are able to decide which techniques to apply. The important point here is that the relationship between ‘practice’ and ‘technique’ is contingent. However, it is more complicated than that. As practitioners gain experience the relationship of ‘theory’ and ‘practice’ shifts, in that the emerging stabilized techniques may become, after analysis and deliberation, the recommended or prescribed way of doing things. Thus, when mastery of the technique is then acquired through teaching (instruction and correction, coaching and training), the employment of that technique will itself be accountable to a set of general principles that provide criteria of correct or incorrect performance. In a way, then, the relationship of ‘theory’ and ‘practices’ becomes recursive (Schmidt 2018a, p. 87).

The concept of ‘practice’ is also dicey in that it, so to speak, abhors generalization. When talking about a ‘practice’, we are specifically concerned with the contingencies to be dealt with in acting in accordance with those general principles. In other words, we are concerned with the particularities of the situation; we are addressing the relationship between ‘plans and situated action’. The concept of ‘practice’ thus escapes the kind of generalization that would be required to make general propositions about the production of social order. ‘Practice theory’ is a proposition that kicks itself in the teeth. However, making generalizations is part and parcel of being a practitioner. The very recognition of an assortment of contingent activities as instances of the same practice is already an act of generalization. In fact, learning to master a practice is to acquire the skill to go on in the same way.
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The methodologically crucial point is this. A relational concept, the concept of ‘practice’ is a *concrete* notion of action, that is, action is conceived of as a unity of manifold determinations. Or in other words, when we conceive of an activity as a practice we are conceiving of it as a *complex*, the study of which necessarily is — ah well, complex. An investigation of a practice involves, of course, observation of bodily conduct, the postures, movements, and orientations of acting bodies in the setting, but also, at the very same time, identifying and characterizing the ‘theory’ constituting the practice. However, there is no gap here: the relation of ‘practice’ to ‘theory’ and vice versa is *mediated*. That is, the study also requires determining the orthogonal or intersecting practices through which the relationship between ‘theory’ and ‘practice’ is mediated. Let me specify.

As already mentioned, the distinction between ‘theory’ and ‘practice’ was developed to deal with problems raised by a form of social division of labor in which the development and curation of technical knowledge and the application of that knowledge is largely separated and distributed. The notion of ‘theory and practice’ is therefore intimately related to the notion of a division of labor. A study of a practice will therefore easily fall short if it focuses on immediately observable conduct without accounting for and determining how the various bodies of interrelated technical knowledge are distributed in the system of division of labor of the wider cooperative work arrangement. The present study will attempt to do so systematically, by addressing what can be called different ‘orders’ of coordination work (Sects. 5–7).

The general principles to which practitioners are committed may be of rather different epistemic status. A practice may involve the application of a theory in the strict sense of a body of scientific (multilaterally corroborated and systematic) knowledge, augmented with models and reinforced by algorithms, or it may depend on science-based technologies with their associated calculi, or on systematically organized empirical knowledge and concomitant models, or on received standard procedures and affiliated protocols, or simply on heuristics proved reliable (‘rules of thumb’). The relationship between ‘theory’ and ‘practices’ will necessarily play out quite differently depending on the epistemic status of the ‘theory’. Thus, conceiving of an array of activities as a practice involves determining the different epistemic statuses of the various forms of technical knowledge involved and the practices of their validation. This sort of determination takes a key place (and a significant amount of space) in the present study.

Conceiving of activities as a practice therefore implies determining the pedigrees of the different bodies of technical knowledge that are involved, whether the ‘theory’ is expressed and transmitted orally, passed down as legends or chants or as

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15 G. W. F. Hegel defines ‘concrete’ as the ‘totality of manifold determinations’ (Hegel 1816, p. 308). However, the way Hegel is using the term ‘totality’ here is a bit exalted. Less exalted, ‘The concrete is concrete because it summarizes many determinations, hence unity of the manifold’ (Marx 1857, p. 36).
situated instructions given in a training situation, or, in a literate culture, expressed and transmitted by means of textbooks, manuals, or inscribed artifacts (from recipes to blueprints). This sort of determination again is central to the analysis of the present study: while scientific metallurgy is crucial to contemporary steelmaking practices, it is made to work in multiple direct and indirect ways that need mapping out.

Conceiving of activities as instances of practices therefore also raises questions of their historical origin and development. Practices constituted by a ‘theory’ in the strong sense of systematic technical knowledge, typically expressed in calculi and transferred in a written form, are practices in a different sense than practices such as artisanal practices constituted by empirical knowledge of radically different epistemic status and expressed in recipes transferred in an oral tradition. This is very much the case in the present study. Grounded in scientific metallurgy, contemporary steelmaking practices are profoundly different in crucial respects from those of traditional steelmaking. We will accordingly spend some effort to give an account of the historical development of steelmaking techniques and practices, showing the vast gap that separates contemporary steelmaking from even steelmaking practices prevalent a mere hundred years ago. Some implications of taking a historical view of practices and conceiving of them as historically specific, will be discussed in the concluding section. However, the present study takes another path than, say, studies in STS that typically aim to uncover the social and technical processes through which a phenomenon in scientific investigations is recognized as a genuine phenomenon and eventually, perhaps, becomes epistemically stable and incorporated as a legitimate piece of scientific knowledge (cf., e.g., Mulkay 1979; Knorr-Cetina 1999). The study at hand is not a study of a practice of discovery but a study of a going concern. It is a study of a family of practices that are based on scientific metallurgy and the technologies based upon it.

In conceiving of activities as practices one has to carefully distinguish the focal practice from related practices that can be said to intersect with the focal practice. We have, for instance, the straightforward practices of cooking a meal or boiling an egg, just as we have practices of teaching cooking, that is, didactic practices. While closely linked, they are surely categorically different, in that the first employs, as a criterion of mastery, knowledge of cooking, while the second also employs knowledge of teaching. That is, when studying practices we are advised to take into account that practices may be complementary and intersect and in that sense form complexes (such as, from the point of view of, for instance production, practices of the lines of work of knowledge curation and teaching and of staffing and planning, but also practices of lines of work such as procurement, inventory control, maintenance, accounting, etc.). In the present study some attention is therefore paid to the wider family of work practices of steelmaking. However, the focal practices of
this study are those of the coordinating the ongoing production, not practices of discovery or didactic practices.

In sum, when conceiving of an activity as a practice, we are in the business of giving what Ryle has dubbed a ‘thick description’: ‘a many-layered sandwich’ at the bottom of which we have the ‘thinnest description’ of behavior in terms of muscular movements and the like (Ryle 1968, p. 482). For example, ‘A statesman signing his surname to a peace-treaty is doing much more than inscribe the seven letters of his surname, but he is not doing many or any more things. He is bringing a war to a close by inscribing the seven letters of his surname’ (Ryle 1968, p. 496). To describe the statesman’s action as an instance of diplomatic practice cannot be reduced to recounting the mere scribbling of a curvy blue line on paper or for that matter to noting the solemn demeanor of the emissaries at the table but involves a host of determinations including those of diplomatic protocol, from the affirmation of the accreditives by which the stateman is taken to represent his or her government, to the selection of approved qualities of pen, ink, and paper, and so on.

1.4  Methodological departures

To reiterate: The aim of our research question is a specific one. It is not about the human condition or about the generic faculties of human individuals or collectives; it is a contribution to the development of computational technologies for coordinative practices, with the specific aim of exploring how we can analyze and describe, cogently and accountably, the ways in which essential aspects of practice — theory and practice, science and art, planning and execution, knowledge and perception — come together in action, not in the abstract, but in one specific family of practices, in the coordinative practices of steelmakers. In this effort, we cannot, without critical examination, take as our foundation and point of departure the dogmas and habits in which the social sciences have found solace. CSCW is home alone.

Let me briefly outline how the study departs from some imported approaches.

There is in CSCW a strong predilection for focusing on ‘small groups’ or ‘teams’ or ‘focused collaboration’ defined by ‘face-to-face interaction’ (e.g., Grudin 1994). This may very well be a symptom of paradigmatic commitments carried over from (in particular anglophone) sociological and social-psychological research where it has been a bedrock assumption that close encounters in ‘groups’ are elemental and foundational. The observation that human bonding involves encounters of the first degree (talk, eye contact, gestures, touch, scent) is surely sound — we are mammals after all, primates actually. But the presumption that encounters of the first degree are somehow the elemental and foundational form of social life, the cell of human society, the site of the production of
‘The Discipline of Steel’: Technical Knowledge in the…

‘moral order’ or ‘social order’, has become sociological dogma. While obviously incoherent (‘face-to-face’ interaction evidently presumes language), the notion of encounters of the first degree as the elemental and foundational form of social life is pervasive in sociological literature from the last 100 years. One finds it in the form of the notion of ‘the primary group’ (Cooley 1909) and later in the notion of ‘the informal organization’ fostered by the Hawthorne studies (Mayo 1933; Roethlisberger and Dickson 1934, 1939; Whitehead 1938). It was promulgated by organizational theorists such as Chester Barnard (1938) and Herbert Simon (1945) and by sociologist luminaries such as Philip Selznick (1948) and Robert Merton (1949). And it was hypostasized in George Homans’ postulate that ‘the [!] human group’ is ‘the most familiar thing in the world’, ‘the commonest […] of social units’ (Homans 1951, pp. 21 f.), a notion subsequently sublimated into dogma in mainstream sociology (e.g., Shils 1951, 1957; Giddens 1984). The dogma of ‘the primary group’ (or ‘the human group’ or simply ‘the group’) as the elementary and ubiquitous unit of human society, based on sentimental bonds and tasked with the formation of ‘solidarity’, lives on, after a fashion, in the idea of the blessings of ‘team work’ that pervades modern ‘human resource management’.

The conceptual limitations of the ‘small group’ paradigm, which dominated mainstream sociology for most of the twentieth century, was perhaps most apparent in the Sociology of Work movement (in the US later rebaptized ‘Industrial Sociology’). Although research in this area produced a large literature (e.g., Chapple 1944; Warner and Low, 1947; Selznick 1949; Walker and Guest 1952; Gouldner 1954a, b; Blau 1955; Chinoy 1955; Blauner 1964; Goldthorpe 1968), one will have to look far and wide to find studies of actual work (Strauss et al. 1985, p. xi; Sharrock and Anderson 1986, p. 85). The research problem was rather framed in term of a distinction between ‘formal’ vs. ‘informal’ organization, which ran parallel to Erving Goffman’s studies of behavior in close encounters versus behavior in ‘public places’ (cf. Goffman 1959, 1961, 1963). In the case of Sociology of Work, the focal interest was with the ‘informal’ or ‘social’ organization as a residue or substrate of non-rational behavior. Fritz Roethlisberger and William Dickson laid down the foundation by introducing a distinction between ‘technical’ and ‘social’. They suggested to use the term ‘technical organization’ to refer to ‘the organization as logically and technically represented by management’, in contrast to the term ‘social organization’ used to ‘refer to the actual human situation’; that is:

‘the actual personal interrelations existing among the employees and between employees and supervisors. It will include the actually existing intricate web of social relations — those that remain at a common human level (friendships, antagonisms, and so on), as well as those that build themselves up into larger social configurations (collective attitudes, practices, and beliefs).’ (Roethlisberger and Dickson 1934, p. 13).
The implicit assumption here — and in the research programs that ensued — is that ‘the technical organization’ is the outcome of rational (‘logical’) design, and thus, belonging to the domain of science and technology, beyond the purview of sociological investigation, whereas the ‘social organization’ and the ‘informal (social) organization’ remained ‘at the common human level’ and thus would be of immense sociological interest. The ideological commitments are obvious.16

Methodologically, this intellectual effort was an exercise in futility. What is characteristic of work, the specific relationships arising in and from dealing with the specific technicalities of the work, were marginalized or simply overlooked: ‘the phenomenon disappears’ (Sharrock and Anderson 1986, p. 16). As already expressed by the German sociologist Heinrich Popitz and his colleagues in 1957 in their now classic study of cooperative work in industrial settings, ‘However one defines the concept of working group, the emphasis is on the grouping of people and on the manner and intensity of this grouping; it leads to distinctions such as “formal” and “informal association”, to diagnosing the “team spirit” or “team climate”’. This is surely not in and of itself uninteresting, but these observations are ‘not specific to the industrial enterprise’ (Popitz et al. 1957, p. 46).

As a result, sociology of work has been generally characterized by an eerie lack of plain ‘objectivity and realism’, to use Egon Bittner’s phrase (1973). Or in the words of Popitz et al. again, ’While the enterprise does afford a rather wide space for informal social relations one should nevertheless not forget that it is first of all a place of work’ (Popitz et al. 1957, p. 42). The reality of work in modern industrial society is that the predominant form of cooperative work is not the ‘working group’ or ‘team’ but cooperative work arrangements of a completely different kind, namely cooperative work constituted by the technical infrastructure or what Popitz et al. refer to as ‘gefügeartige Zusammenarbeit’, i.e., ‘structural cooperative work’ (Popitz et al. 1957, p. 46 et passim). By focusing on ‘informal relations’ in ‘groups’, the Sociology of Work movement by and large relegated that overwhelming reality to limbo.

Structural cooperative work is especially pronounced in industrial settings such as manufacturing, construction, agriculture, mining, metallurgy, chemical production, transportation, energy production, etc., and in clinical settings, too,

16 European sociology was to a large extent spared the shackles of the ‘primary group’ paradigm, especially German sociology of work (e.g., Popitz et al. 1957; Kern and Schumann 1970; Mickler et al. 1976; Mickler 1981; Kern and Schumann 1984). The same applies to Francophone cognitive ergonomics (e.g., Ombredane and Faverge 1955; Faverge et al. 1958; Montmollin 1991; Leplat 1992, 1993; Montmollin 2001). As argued by the German sociologist Helmut Schelsky (1954), the reason for this remarkable difference is that Industrial Sociology should be seen as a an ideologically motivated movement, particular to the US, that strove to address what in Europe was known as the ‘social question’, by measures internal to the corporation (ultimately in the form of Human Resource Management), in contrast to the social reform policies pursued by European Socialism.
in so far as clinicians primarily orient to the state of the patient. But that is not
the point here. We are not in the business of building a typology of work. The
point is rather that structural cooperative work and hence structurally organized
coordination is the background against which discursively organized coordina-
tion plays out. If that background is disregarded, the ‘the phenomenon is lost’.

As a conceptual framework for studying work practices, the notion of ‘small
groups’ as the elementary and generative cell of social order is intellectually
numbing. How work is actually done, how it is planned, how plans are made to
work, how contingencies are identified and dealt with, how work is timed, how
state changes are mediated by and propagated via the technical infrastructure,
from one worker to the next, what technicalities workers must know and master
in their line of work — all this was beyond ‘sociology of work’ as its proponents
understood it; such matters were left for Production Engineering to worry about.
Consequently, the Sociology of Work movement has brought us nowhere when
it comes to studying cooperative work ‘in the wild’. It abandoned objectivity and
realism by focusing on the ‘common human level’.

In passing, it may be relevant to also mention an emerging school of thought
in the area of Organizational Studies (e.g., Feldman 2000; Feldman and Pent-
research on ‘business processes’ (e.g., Malone et al. 1993; Malone et al. 1999),
this research tradition aims to explore how organizational practices (somewhat
misleadingly dubbed ‘routines’) are a font of organizational innovation and
change. This approach may have merit in as much as practitioners, as they daily
handle contingencies, that is, in the mundane experimentations coping requires,
surely are a source of essential experiences: a source of a kind of organizational
mutation. However, for the purpose of investigating cooperative work prac-
tices, especially with respect to issue of the role of the technical knowledge and
skills employed by practitioners in coordinating their distributed activities, this
research generally misses the boat. The problem being that it, in rectilinear con-
tinuation of the traditions of Organizational Theory and Sociology of Work, work
from a managerialist position and thereby does not acknowledge that the criterion
of what constitutes a practice is internal to the practice and that the issue of what
the criterion might be is an empirical question (as pointed out by Bittner 1965).
This clearly illustrates the problems one may encounter when striving to apply
the concept of ‘practice’ systematically without taking the relational character of
the concept of ‘practice’ seriously and thus without addressing the issue of the
criterion of sameness, as constituted by the ‘theory’ to which the practice is com-
mittted. For example, in a widely cited article by founding authors of this tradi-
tion, we are told that ‘Practices are carried out against a background of rules and
expectations, but the particular courses of action we choose are always, to some
extent, novel. In this sense, practice is inherently improvisatory’ (Pentland and
This is a quite bewildering proposition. Saying that the performance of practice is ‘to some extent, novel’ and even ‘inherently improvisatory’ begs the question: ‘novel’ and ‘improvisatory,’ according to which criteria? This question is not addressed, however, which empties the sentences of content. In short, the problem this tradition faces is that it, instead of investigating the ways in which workers go on and do the same in the face of contingencies and the criteria of sameness they accept and apply in doing so, simply ignores the issue. Or even dismisses it: we are, for instance, told, in the introduction to a special issue on ‘routine dynamics’, that ‘studies of routine dynamics based in fieldwork have dissolved the illusion of sameness’ (Feldman et al. 2016, p. 505). The authors apparently do not realize that they, by talking about ‘routines’ and ‘practices’ and yet rejecting the notion of ‘sameness’ as an ‘illusion’, abandon any claim to ‘practice theory’, not to mention to empirical studies of cooperative work and coordinative practices.

In hindsight, seen from the vantage point of CSCW, a way out of the futility of sociological theorizing can be said to have been opened by Conversation Analysis (CA). Although taking interaction in small groups as its point of departure, CA departed from these approaches by subjecting ordinary conversation to rigorous investigation. Instead of prose renditions of affective reactions, it restricted itself to uncovering and describing the logic of the normativity underlying the orderly progress of a conversation, by devising and applying a systematic notation to analyzing conversations in their constituent parts (Sacks et al. 1974). However, CA could only take us so far. As pointed out by Wes Sharrock and Bob Anderson, Conversation Analysis was equally ill-fitted to serve as an approach to the study of work practices: ‘The admirable thing about conversational analysis is not the generality of its methods, but their specificity. Conversational analysis has not provided methods for the analysis of social organization, or even of social interaction, it has provided methods for the analysis of conversation’ (Sharrock and Anderson 1986, p. 80). That is, the notion of the ‘sequential organization’ of ordinary conversation that underpins CA has a strictly bounded jurisdiction, namely, ordinary conversation organized by turn-taking, and it thus cannot, without endless conceptual fiddling, be generalized and posited as ‘formal structures of practical action’ that are presumed to somehow engender order (as was suggested in, e.g., Moerman and Sacks 1971; Sacks et al. 1974).

However, closely related to CA in terms of its insistence on the local nature of the production of order, Ethnomethodology may be seen as having begun as an attempt to put research of close encounters on a rigorous footing, for instance and most famously, by (ostensibly) exposing the normally tacit normativity of ordinary life in the famous ‘breaching experiments’ (Garfinkel 1967), but departed from it in its ‘studies of work’ program, by insisting that an account of a work practice must be expressed in a language that is demonstrably adequate to that practice, in terms of the technical knowledge underpinning it, and not in terms of,
say, ‘small groups’ or decontextualized conversation (e.g., Heritage 1984, Chapter 9; Lynch 1985; Garfinkel 1986; Sharrock and Anderson 1986, Chapter 6). 17

This jailbreak attempt, as it were, became a fully-fledged program shift in the context of CSCW as studies of work were undertaken with the clear aim to investigate actual work practices, and to do so systematically, in order to inform the design of computational technologies for cooperative work settings (e.g., Suchman 1983, 1987; Suchman and Wynn 1984; Hughes et al. 1988; Harper et al. 1989a, b; Heath and Luff 1991, 1992; Harper and Hughes 1993).

However, more often than not, CSCW studies of work have remained focused on or have remained restricted to those rather special types of work that are discursively organized (i.e., where the job consist in talking to people, such as work at emergency centers and help centers) or can be seen as substantially coordinated by conversations (for instance, in auditors’ meetings with bookkeepers, budget negotiations, project meetings, etc.). It is indicative of the strong gravitational pull of the discursive practices paradigm that CA-informed studies of ‘professional vision’ in fact steer clear of professional perception that is not discursively organized but instead, with remarkable acuity, focus on cases where different actors debate the meaning of a visual scene (see, e.g., Goodwin 1994, 2000). Even in the case of structural cooperative work, which cannot in any meaningful sense be said to be discursively constituted or organized and where the structure and dynamics of the technical apparatus and processes play an important role — as a challenge or as an affordance — in coordinating the cooperative effort, the technical aspects are often dealt with only schematically and marginally. As a rule, the representation of discourse takes center stage, as was it a script for a theater play, with annotations of noises in the wings and actors’ fiddling with props. But as the renowned Ethnomethodologist Michael Lynch has argued, studies of conversation are a ‘double-edged’ resource for studies of specific work settings because they, while providing ‘an easy way to produce analytical findings’, in fact leave ‘the specific and substantive character of the work being done in-and-through the conversation unexplicated’ (Lynch 1985, pp. 8 f.). A fortiori, ‘structural cooperative work’, or cooperative work performed without ongoing conversation, by reciprocally or serially changing the state of some material system, or in which discourse plays a subordinate role, is left completely in the dark. The crux of the matter is that the world of ordinary work is enormously heterogeneous, and that it is just as dogmatic to assume that work is always, and in principle, discursively or ‘sequentially’ organized, as it is to presume that the concept of ‘group work’ or ‘teamwork’ is foundational to studies of cooperative work.

17 Egon Bittner’s article on ‘The concept of organization’ should probably be seen as a precursor to the ‘studies of work’ program (Bittner 1965).
The upshot of importing these discourse-focused traditions into CSCW is that workers’ technical knowledge and their familiarity with the infrastructure of the setting tend to be bracketed by methodological fiat. For all practical purposes, that is, discursive conduct has been granted privileged status in CSCW research. This, I submit, is a major reason why the observation, referred to by the term ‘mutual awareness’, that workers normally manage to coordinate their cooperative effort routinely, without incessantly interrupting their work to contemplate and deliberate, has remained a puzzle.

However, outside of the jurisdiction of sociological studies of work, with its preferences for discursively organized interaction, cooperative work in complex technical settings have been studied extensively.

There are of course studies of cooperative work that, for long stretches by and large, proceeds in an orderly fashion without ongoing discourse or consultation of written proxies or coordinative artifacts. Lars Rune Christensen gives an illuminating example of such coordinative practices in the cooperative effort of building an interior wall: the carpenter erects the steel frame and the first plasterboard whereupon the electrician takes the result of the carpenter’s work as the starting point for his or her work and in turn leaves the work-in-progress to the carpenter to erect the second plasterboard, ultimately leaving the now closed interior wall to the painter, all the while without the successive workers’ necessarily engaging in conversations or similar semiotic exchanges (Christensen 2014, pp. 14–16). However, the author’s aim is to explore the extent to which the entomological concept of ‘stigmergy’ may be useful as a model of coordination work mediated by successive changes to the state of the field of work, and in pursuing this aim, he is of course entitled to elide the issue of the categories of states workers take heed of and orient to. But by the same token, this study does not help us much here. Furthermore, given that our problem is to determine the categories in terms of which workers orient to, perceive, and reason about their work, construction work may not be the most advantageous study domain. The temporal structure of construction work may complicate our investigation in as much as the lapse time between interventions by different workers in the course of the construction process may be protracted. It may thus very well may be difficult to ascertain the extent to which work is being discursively organized between interventions. By contrast, process control work as a study domain has the obvious advantage that it, for long stretches, is characterized by high-frequency state-changes and that interventions typically come about as immediate reactions, without intermediate discourse and consultation. This then makes it less complicated to foreground the perceptual competencies involved in coordinative practices and determine the categories in terms of which workers orient to and heed the work of others.

The present study happens to be situated in a vast array of studies of work that, although they differ with respect to research objectives, conceptualizations
of work, and the particular domain of work, have in common that they address
the logic of which basically is concerned with control of dynamic processes.

In the early days of computing technology (from the early 1950s to the late 1980s),
before the ubiquity of inexpensive access to computational capacity made interactive
and networked computing economically viable, computational capacity was typically
deployed in a modality one could call ‘wall-to-wall’ computing (Schmidt 2011, p.
412): the computer system incorporated a model of a process (e.g., air defense, airline
reservation, power plant control, payroll calculation) and the task of operators then
was to feed the system with data to keep it running and otherwise take care of the
results of its calculation and whatever fell outside of the boundaries of the underly-
ing model. This computing paradigm — popularly dubbed ‘automation’ — raised a
host of sociological concerns that generated several important research traditions. To
mention but the most important contributions and traditions. On the one hand, a large
number of social-science studies of experiences with ‘automation’ were particularly
concerned with the implications of automatic control for ‘alienation’, ‘deskilling’, and
unemployment (e.g., Bright 1958; Amber and Amber 1962; Blauner 1964; Pollock
Shaiken 1984; Zuboff 1988; Bergman 1995; Perby 1995). Related to these studies,
the Francophone ergonomics tradition produced in-depth field studies of operators’
competencies, reasoning, knowledge (e.g., De Keyser 1988; Kasbi and Montmollin
1991; Van Daele and De Keyser 1991; Decortis 1994). On the other hand, early stud-
ies in ‘man–machine systems’ research, concerned with the design of anti-aircraft
artillery and airplane cockpit design (Singleton 1974), evolved into an interdisci-
plinary research area, involving both control engineering and cognitive psychology
and devoted to studies of operator work in, typically, computer-controlled large-scale
technical systems, that generated a large body of studies concerned with, initially,
operators’ ‘mental workload’ (e.g., Edwards and Lees 1974; Sheridan and Johannsen
1976; Bainbridge 1978; Moray 1979; Johannsen and Rijnsdorp 1983), and, subse-
duently, operator decision making and interface design (e.g., Hollnagel 1980; Holl-
nagel et al. 1981; Rasmussen and Lind 1981; Woods et al. 1987; Rasmussen and

While the present study addresses process-control work and work in control
rooms and in doing so draws on these traditions (with gratitude), the present study
diverses from the dominant analytical framing of these traditions in that it does
not focus on the issue of ‘allocation of function’ or the ‘interaction’ between ‘auto-
matic machinery’ and ‘human operator’. It focuses on the role of technical knowl-
edge in coordinative practices. The present study also diverges from many of these
traditions in that it does not, as is paradigmatic especially in ‘human–machine sys-
tems’ research as well as in the broader sociological literature concerned with the
(putatively shrinking) place of humans in a world of machines, conceive of ‘auto-
matic machinery’ and ‘human’ as commensurate ‘system components’ or similar.
This notion, I submit, amounts to a category mistake. Computational artifacts are
technical complements of our practices, and beyond the bounds of these they are just junk (Schmidt 2011, Chapter 13; Schmidt and Bansler 2016). Imagining ‘automatic machinery’ as something beyond the bounds of humanity, some alien agency (e.g., Winner 1977, 1983), may of course provide materials for thrilling ghost stories, but in the everyday world of work the dreadful image of ‘the incredible shrinking man’18 induces us to overlook workers’ mundane skills as manifested in their (often arduous but normally successful) appropriation and integration of these artifacts as technical complements of their practices.

It is more relevant to mention a number of more specialized contributions to the study of cooperative work in highly dynamic and time-critical environments such as vehicle-control work. A series of organizational-sociology studies of complex operations such as aircraft carrier flight control (Rochlin et al. 1987; Weick and Roberts 1993; Rochlin and von Meier 1994; Rochlin 1997) have focused on identifying configurations of the work organization that afford ‘high-reliability operations’ in the face of dramatic contingencies, but they do not, however, offer in-depth analysis if the coordinative practices that afford that achievement. This is in contrast to studies such as Ed Hutchins’s studies of the cooperative work of maritime navigation (Hutchins 1995) and of aircraft control (Hutchins and Klausen 1996) that provide us with rigorous and rich accounts of how representational artifacts, from sensors to charts, are employed by the members the cooperative ensemble on the bridge of a naval vessel or in the aircraft cockpit to keep one another continually updated, by means of speech or mutually visible or migrating graphical representations. However, as is generally the case in the literature at large, these studies are limited to discursively organized coordinative practices. In addition, while the studies set out to investigate skilled practices ‘in the wild’, in contrast to the paradigmatic insistence on laboratory experiments in cognitive psychology, the studies were amputated conceptually, as studies of actual practices, by their attributing agency to ‘representational states’ that are conceived of, as it were, as ghostlike entities that retain their integrity while propagating through ‘a functional system’ consisting of the minds of team members and the various instruments of the bridge or the cockpit (Hutchins 1995, pp. xvi, 49, 117, 154; Hutchins and Klausen 1996, p. 27). This conception is predicated on the methodological preference of considering the cooperative work effort as a ‘computational functional system’ and accordingly reduces practice to the ‘implementation’ of an algorithm. As Hutchins explains his approach, ‘The system formed by the navigation team can be thought of as a computational machine in which social organization is a computational architecture’ (Hutchins 1995, pp. 165, 185, 226 et passim). The accomplishment of order, which is what is to be explicated, is already presumed.19

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19 Tim Ingold (2000) and Graham Button (2008) offer different but consonant critical discussions of Hutchins’ functionalist-cognitivist account of the practices of maritime navigation.
Finally, of course, we have a large body of CSCW and similar studies of cooperative work practices in ‘centers of coordination’ (Suchman 1997) such as air traffic control centers (e.g., Hughes et al. 1988; Harper et al. 1989b, 1991; Harper and Hughes 1993; Halverson 1995; Berndtsson and Normark 1999), urban rapid transit control centers (e.g., Heath and Luff 1991, 1992, 1996; Filippi and Theureau 1993; Sanne 1999), emergency management centers (e.g., Samurçay and Rogalski 1993; Whalen 1995; Normark and Randall 2005; Pype et al. 2014); and airline coordination centers (e.g., Suchman 1993; Goodwin and Goodwin 1996; Suchman 1997; Redaelli and Carassa 2018). Although Hutchins’ abovementioned study of coordinative practices on the bridge of a naval vessel only peripherally addresses interactions between the ensemble on the bridge and at other stations of the ship, it may be seen as belonging to this category. These work settings are, like steelmaking, characterized by work in control rooms dealing some external events and processes, but in contrast to the control of transformation processes such as generating electrical power, brewing beer, or making steel, work in centers of coordination, essentially, ‘is dedicated to the ongoing management of distributed activities in which one set of participants is charged with the timely provision of services to another’ (Suchman 1997, p. 114). That is, we are dealing with practices of a different category. In the case of centers of coordination, we have settings in which activities of mobile or stationary workers at various locations outside of the control center are deployed, directed, and aligned by actors at the center, whereas the work of controlling transformation processes, essentially, is devoted to maintaining the boundary conditions of a fundamentally automatic causal process. This has significant implications, as we shall see.

In any event, these studies focus on settings in which the coordination of the cooperative effort is largely discursively organized. In contrast, the workers at the steel plant generally are unable to monitor the bodily conduct of each other and talk to each other, and the virtually effortless coordination and alignment of activities we will observe in the following therefore cannot in any meaningful way be said to be discursively constituted or organized. The aspects of their coordinative practices that hinge on their understanding of the web of processes in which they are engaged are not, as it were, drowned out by ongoing talk or by the displaying and monitoring of bodily conduct. This makes it methodologically feasible to foreground and identify the domain-specific knowledge that enables workers to heed the changing state of the technical processes as they go about their own local activities. It makes it feasible to identify the categories in terms of which their coordinative practices are organized.

To answer our question — how do the steelworkers manage to coordinate and integrate their distributed activities? — the study examines the ways in which the coordinative practices of steelmakers hinge on not only their knowledge of the plant and its idiosyncrasies, their training and experience, but also on the knowledge of the metallurgy of steel they have acquired through their in-house education and instruction and on their ensuing skilled perception, as well as on the advances of the metallurgy of steel (especially in the course of the last few decades of the
twentieth century), as incorporated in the overall design of the plant and of the processes, and as represented in the timing schemes and alloying protocols and in the measurement instruments and control systems. Consequently, their coordinative practices cannot be understood without at least a cursory understanding of the metallurgy of steel as represented in the their education and in the design of the plant and its processes and procedures. For this reason, I must ask the reader to bear with me if the following, at times, seems densely technical. It may serve as a consolation that my rendition of the technical knowledge involved is, in fact, only a digest.

2 A tour of the steel plant

The production facilities of the Danish Steel Works are situated in Northern Zealand, on a small peninsula where Roskilde Fjord joins Ise Fjord immediately before the latter meets the sea of Kattegat. The site is a sprawling complex of plants, spread-out around along the shore of the bay that forms a natural harbor. Situated in the northern part of this complex, on a narrow peninsula in the bay, the Steel Plant is easily recognizable. It is a relatively new construction of several connected buildings of which the main building, housing the production shops, is a huge white building that can be seen from far away (Figure 1).

Having passed the gate, you drive up to the Steel Plant by a winding road along the shore, under a bright and windy sky with fleeting clouds and hovering seagulls. Entering the plant, you leave behind the glimmering sea and the salty breeze and — having put on working clothes, safety helmet, and steel-capped boots — find yourself in an entirely different world.

The interior of the building is in partial darkness, because of dust and dirt on windows and lamps and smoke in the air. Instead, the place is illuminated locally and intermittently by red-hot electrodes, by the flickering intensely white light of liquid steel, and by glowing sparks of slag flying from furnaces. You are surrounded by a cacophony of alien and eerie noises: a den of humming, rattling, and gnarling sounds, interrupted by sudden thuds and bangs, and blaring sirens. With an acute sense of disquiet you realize the vastness of the place and the equipment, and that, far above you, cranes are carrying vessels the size of trucks containing liquid steel or slag, making the floor vibrate as they move along.

In this regard, as far as the visitor’s first impressions are concerned, nothing much has changed since James Nasmyth observed the production of iron in the Black Country of England in 1830:

‘By day and by night the country is glowing with fire, and the smoke of the ironworks hovers over it. There is a rumbling and clanking of iron
forge and rolling mills. Workmen covered with smut, and with fierce white eyes, are seen moving about amongst the glowing iron and the dull thud of forge-hammers [...] The workmen within [the furnace shops] seemed to be running about amidst the flames as in a pandemonium; while around and outside the horizon was a glowing belt of fire, making even the stars look pale and feeble.’ (Nasmyth 1883, pp. 163-165).

A century and a half later, that awesome spectacle of steel-making has not changed much. In the mid-1970s, a young man, Verner Jensen, who later became leading shop steward for the entire DDS, was offered a job as a smith’s assistant tasked with furnace repair work:

‘I didn’t know what it was all about, repairing furnaces, but I accepted the job offer. And the foreman was mighty decent, so I thought, “Well, you begin Monday”, and so I did.

When I arrived to repair furnaces and entered the furnace shop, I didn’t believe that anything like that existed. I thought, “It’s something like… it’s just like Dante’s hell”, or something like a description of hell. It was completely dark, and there was smoke everywhere, and there was an infernal racket. Cranes were running over the floor — they didn’t touch the floor but they were moving at an incredible speed. I thought, “This here, you won’t survive that
for three days. There is nothing else to do but to keep at a little distance and find something else to do at some time”’. (Jensen 2003, 00:07:30–00:08:23).

The first impressions of witnessing steelmaking in action are indeed overwhelming: The hellish sounds and sights, the smells, the superhuman scale of things, the acute sense of human fragility; it is all beyond ordinary experience and quite perplexing.

And yet, in spite of the scale of everything and the noise and smoke and sparks, work in contemporary steel production requires the utmost precision and accuracy. In the words of a metallurgist, ‘steelmaking has now become a hi-tech industry’ (Llewellyn 1994, p. 11). It is heavy industry, but in its contemporary form the production of steel is also an applied science. The ‘secret of steel’ has been cracked.

2.1 The steel plant
The Danish Steel Works Ltd. was established in 1940, located in a coastal town with a long history of iron industry. Steel production was commenced in 1942, during the Second World War. From the very beginning and until the late 1970s steel was produced in Siemens-Martin furnaces (also known as ‘open hearth’ furnaces). This furnace technology, which was very much the standard from the late nineteenth century and well into the second half of the twentieth century, was a versatile technology that could use coal, gas, and oil as energy sources and handle a broad spectrum of ferrous feed, from ore to scrap. But the melting process was slow: At DDS, to melt a charge took 7–8 hours (Burchardt 2009, p. 173).

From the mid-1970s to the mid-1980s, the plant was renovated. In short order, radically new steel technologies were introduced. The Siemens-Martin furnaces were phased out from 1975 until 1980 and replaced by a new facility for producing steel based on two ‘electric arc furnaces’ (EAFs), each with tap-to-tap time of about 75 min. The new furnaces became operational in 1976. Experiments with continuous casting were undertaken immediately after, first by casting one charge at a time, subsequently stepwise increased to 4–5 charges per run. In 1980, a new continuous casting machine for billets was inaugurated (see Figure 2). Finally, to bridge the gap between the batch-oriented temporal order of the furnaces and the new temporal order of continuous casting, a ‘ladle furnace’ was introduced in 1985–86 as an intermediary station, tasked with adjusting temperature and alloy quality for casting. This increased the plant’s capacity to more than 800,000 t/y (DDS 1994, 1998).

This technical configuration was by and large the setting in 1997–98 when the fieldwork was conducted. At that time, the plant was considered one of the more advanced steel plants. It was exemplary with respect to environmental protection and working conditions (Plöckinger and Etterich 1985, pp. 468–471), and by adopting the novel ladle furnace technology in 1985–86, it had become one of
Figure 2. Plan drawing of the Steel Plant, 1975 (cross-section). The new electric arc furnaces are in the leftmost hall (only EAF A is visible here). The casting station is the curved apparatus center-right; the ‘tower’ is immediately to its left. The Ladle Furnace is not in the plan drawing as it was only installed ten years later, in the middle hall, against the sound-proofed wall of the hall housing the EAFs. (Engineering drawing by DEMAG, reproduced in Plöckinger and Etterich 1985, p. 469).
the only about 200 steel plants applying that technology globally (the first ladle
furnace was installed as late as 1965, Amblard and Legrand 1988). At the time of
the fieldwork, the plant produced about 800,000 tons of crude steel annually, to
the tune of an annual energy consumption amounting to about 460 MWh, or 475

Production at the Steel Plant involves a series of processes. The major pro-
cesses are these:

(1) Collection of scrap: Sorted scrap is collected in the ‘scrap yard’ and transported by crane
to one of the two EAFs.

Figure 3. Schematic floor plan of the Steel Plant (not to scale). Grey areas represent ele-
vated platforms, the darker the higher the elevation. The major steps in the process are described in
the text below and are indicated by numerals in ovals. — The deployment of staff is only roughly
indicated by matchstick figures.
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(2) **Melting**: Scrap iron and steel is melted in the two EAFs, and impurities such as phosphorous are removed.

(3) **Tapping**: Steel is tapped into a ‘ladle’ positioned on a ‘ladle car’ and initial refinement of the melt is started.

(4) **Refinement and alloying**: Remaining impurities such as sulfur are removed, alloying elements are added to the molten steel to achieve the required alloy quality, and the temperature is adjusted; this is done at the ‘ladle furnace’.

(5) **Casting**: The steel is eventually cast at one of two ‘continuous casting’ (or ‘string casting’) machines, casting slabs and billets, respectively.

The various processes of steel production are managed by an ensemble of actors deployed as follows to the different stations (cf. Figure 3): ① **the Scrap Yard**: one or two crane drivers; ② **Electric Arc Furnaces**: two furnace operators in the EAF control room (one for each furnace), two ‘melters’ (doing various work outside of the control room, e.g., taking samples from the furnaces), one ‘slag pot man’, and one or two ‘hole men’ (primarily doing work related to tapping the steel ③), and one crane driver servicing the two furnaces (delivering scrap, lifting electrodes, moving slag pots, etc.); ③ **Ladle Furnace**: one operator in the control room and one assistant (doing various work outside of the control room, e.g., taking samples of the melt), and one crane driver servicing the Ladle Furnace (delivering ladles with molten steel for processing and taking them to the casting station afterwards); ④ **Casting**: five or six workers at each machine, working both inside and outside of the control room; and finally six workers in the next hall for cooling slabs and billets, cutting, and adjustment (outside of the diagram in Figure 3, to the right of the casting machines in Figure 2). Altogether, a shift requires about 35 workers deployed at the various stations, plus maintenance workers,

![Figure 4. The Scrap Yard. Left: Scrap is picked up by magnet. Right: Scrap is placed in a ‘basket’.](image-url)
K. Schmidt

foremen, engineers, etc. That is, the workers involved in the overall process of steel production are highly distributed spatially.

2.1.1 The scrap yard

Our tour begins outside of the Steel Plant building, in the ‘Scrap Yard’ (indicated by ① in Figure 3). Here scrap iron and steel has been received from external vendors, carefully sorted according to composition, form, and mass, and finally stored in large bins (Figure 4). Special care is taken to identify and remove copper and aluminum from scrap, as these metals typically are considered a source of contamination in steel.

The first step in the steel production process is the selection of scrap from these bins. A selection is picked up by an electromagnet crane and placed in a large steel container called a ‘basket’. When the required amount has been

Figure 5. Electric arc furnace, plan drawings. Tapping hole is on the left, slag hatch on the right. (Source: Photo copies of plans in Steel Plant’s internal tutoring materials).
picked up, the basket is transported by an overhead crane to one of the two electric arc furnaces (indicated by ② in Figure 3) for melting and purging.

2.1.2 The electric arc furnaces: melting and purging

Each electric arc furnace (EAF) is a squat, cylindrical vessel made of heavy steel plates and a dome-shaped roof (Figure 5). The charge is heated by a set of three electrodes that reaches down through the roof and yield 70 MW. The vessel sits on a hydraulically operated rocker that tilts the furnace forward for tapping and backward for slag removal. The walls and the roof of the furnace are made of water-cooled panels lined with refractory, whereas the bottom of the vessel, the hearth, is lined with magnesium oxide (MgO). Each of the two furnaces can handle a charge of about 110 tons, in addition to a permanent ‘swamp’ of about 20 tons of melt at the bottom.

The furnace is charged from the top, and for this purpose both the roof and the electrodes can be lifted out. When a furnace is ready for charging, its roof is

Figure 6. Electric arc furnace. Left: Roof lifted. Right: Scrap is released from ‘basket’.

Figure 7. Electric arc furnace. Left: Charge being treated with oxygen through the slag hatch. Right: View from EAF control room while oxygen treatment is ongoing.
removed and scrap iron dumped into the furnace (Figure 6). Charging is done in two steps because scrap is far more voluminous than liquid steel. The first basket holds about 60 tons, and when the scrap from the first basket has been ‘just about melted’, which normally takes about 30 min, a second basket of about 48 tons is added. The two baskets now constitute one ‘charge’.

Apart from melting the scrap, of course, the overriding objective of the EAF operators is to purge the melt, that is, to remove impurities, in particular phosphorous. The method for achieving this is called ‘basic electric arc steelmaking’ and essentially consists in creating an environment rich in oxygen, by combining the formation of a basic (or alkaline) slag with the blowing of oxygen. To produce a basic slag, carbon, lime (CaO), and ‘dolomite’ (a mixture of CaO and MgO) is added to the charge with the first basket. This slag reacts with the foreign elements in the melt such as and especially phosphorous. ‘Slag is the detergent of steel’, I was told. In addition, as the first basket is being melted down, oxygen is blown into the steel by an ‘oxygen lance’, i.e., a refractory-covered steel pipe, which is inserted into the furnace through the slag hatch in the rear of the furnace (Figure 7, left). The combined effect of these measures is, technically, that phosphorus is removed by oxidation to the pentoxide ($P_2O_5$) which then combines with the lime to form a phosphatic basic lime slag.

The formation of slag, in addition to binding impurities in the slag which then rises to the top of the melt, also helps to inhibit the dissipation of energy and the reabsorption of furnace gasses into the melt. The blowing of oxygen has the additional benefit of raising the temperature in the melt considerably, in particular through oxidation of carbon, which in turn speeds up the melting process. The evolution of carbon monoxide in the melt, which is fittingly called ‘the boil’, in turn stirs the melt and thereby promotes the washing out of slag from the melt.

When the second basket has been added to the charge, oxygen is again blown into the melt. When the operator believes that the steel has been melted and the temperature of the melt has reached about 1540 °C, a sample of the melt is taken

Figure 8. Left: Charge being tapped into ladle. Right: Ladle in ladle car during tapping.
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and sent to the laboratory for analysis. The laboratory will return an analysis report (via a terminal linked to the laboratory’s computer system) in about five minutes. In the meantime, the melt is heated up while the blowing of oxygen is continued. When the analysis report has been received, it is checked, especially for the phosphorous and carbon values, and if required the blowing of oxygen continues.

When the temperature has reached 1580–90 °C, a second sample of the melt is sent to the laboratory for analysis. When necessary, for instance if the analysis indicates that the phosphorous content is still too high, slag is removed, but otherwise the slag is left in place until later, as it protects the walls of the furnace and helps to keep the temperature high.

About 45 min after the second basket, when the operator is satisfied that the desired quality and temperature have been reached, the charge is tapped.

2.1.3 The ladle car: tapping and refining

Before tapping is begun, several things are done more or less in parallel.

For purposes of further processing and transportation the melt will be tapped into a movable container (Figure 8, left). The ‘ladle’, as it is euphemistically called, is an open-topped cylindrical vessel the size of a small truck. Its walls and bottom are made of heavy steel lined on the inner wall with concrete and, higher up, refractory brick (‘stone’).

Between each charge, ladles are renovated at the ladle preparation station and preheated to about 1000 °C. When a renovated ladle for the charge to be tapped is selected, the ladle preparation operator informs the EAF operator of its ID code as well as its current temperature and the thickness of the ‘skull’, i.e., the cake of solidified steel at the bottom of the ladle that has accumulated from previous charges. On the basis of this, and on the basis of his knowledge of the position of the charge in the production sequence (i.e., will it have to wait and for how long?), the EAF operator decides on the appropriate tapping temperature (normally 1620 °C, but occasionally up to 1730 °C) and adjusts it accordingly. Just before tapping, the renovated ladle is fetched at the ladle preparation stand by crane and placed upon a large railcar which is simply called the ‘ladle car’ (indicated by ③ in Figure 3).

At about the same time, also just before tapping, the EAF is tilted backwards to remove the furnace slag as this contains large amounts of oxides (MnO and FeO) and impurities (P₂O₅) which would contaminate the steel if not removed. The railcar with the ladle is rolled-in underneath the furnace. That done, the furnace is tilted forward so that the tapping hole is just above the ladle in the car. The ‘hole man’ opens the tapping hole, and the liquid steel teems into the ladle (Figure 8, right). When tapping is finished, the furnace is tilted back to level position to be readied for a new charge, and the ladle car with the now full ladle is rolled into the adjacent hall housing the Ladle Furnace (indicated by ④ in Figure 3).
Also at the same time, while the tapping procedure is initiated but before tapping, several steps have been taken to prepare the charge for further refinement while the ladle is on the car, waiting to be moved on to the next station (the Ladle Furnace).

As described above, oxygen was lavishly blown into the melt during the melting processes in order to remove phosphorus and to raise the temperature (by burning carbon). As a result, when the melt is tapped, it contains large amounts of oxygen (in the form of carbon monoxide); sometimes, in fact, the oxygen content is so high that the melt is literally seething. Therefore, just before tapping and in order to remove all that oxygen from the melt, the ‘hole man’ will dump aluminum, which has a very high oxygen affinity, into the ladle (unless, that is, the charge is to result in a product in which aluminum is unwanted, in which case silicon is used). This treatment results in what is called ‘killed’ steel; or, to use a literal translation of the very apt Danish expression, the ‘wild’ steel is ‘calmed down’ (‘beroliget’).

Furthermore, also just before tapping, a mixture of fluxing lime (CaO) and fluorite (calcium fluoride, CaF₂) was placed in the empty ladle, in addition to aluminum. As a result of this, a new slag is formed, consisting of primarily lime and fluorite, which is a ‘reducing’ as opposed to the oxidizing furnace slag. This is done for several reasons, in part in order to achieve very low levels of sulfur, partly because fluorite lowers the melting point of the slag, thereby reducing its viscosity and increasing its reactivity.

And again before tapping, the ‘hole man’ may also have added ferromanganese, silicon-manganese, or ferrosilicon to the ladle, depending on the outcome of the second analysis together with the target quality of the ultimate product.

Finally, after tapping and the addition of fluxes, compressed argon can be blown through the melt from a porous stone in the bottom of the ladle. Argon is an inert gas and thus does not affect the composition of the steel, and the blowing of argon through the molten steel serves the purpose of stirring the steel to speed up the chemical reactions, to ensure a uniform temperature and chemical composition throughout the melt, and to purge the steel of the inevitable slag enclosures by gently escorting them to the surface, to the slag. This procedure is called ‘soft bubbling’. After a short period of, say, 20 min of stirring, the slag will be ‘thin and fluid’, as it was expressed to me, and ‘much easier to handle, in that all of the compounds now are dissolved in the melt; the steel now does not harbor any surprises’. The ‘soft bubbling’ procedure on the ladle car is activated by the ‘hole man’ or the ‘melter’, in connection with tapping the charge, or by the Ladle Furnace operator, from a small control panel behind her chair.

The point of all this is to exploit the waiting time to prepare the charge further, while it is on the car, and reduce the time required at the Ladle Furnace.
Figure 9. Ladle furnace plan drawings. Waiting position is on the left, the active position with electrodes on the right. (Source: Photo copies of plans in Steel Plant’s internal tutoring materials)

Figure 10. Ladle furnace. *Left*: Front view from shop floor. *Right*: A view from the top: charge with black slag, argon ‘bubbling’.
2.1.4 The ladle furnace: refining and alloying

At the Ladle Furnace (indicated by ④ in Figure 3) the steel is readied for casting. What is to be done at this stage depends on two variable factors: on the one hand, what has been accomplished with the charge at hand in the previous processes, and, on the other hand, what is required by the casting process and with respect to the quality of the final product. Roughly, though, the job of the Ladle Furnace is to deoxidize the charge, remove sulfur, add the requisite alloying elements, and adjust the temperature.

The ladle furnace (Figure 9) is a turntable construction with two diagonally opposite positions, a waiting position and a processing position (Figure 10, left). When a new charge arrives, the ladle is placed at the waiting position and covered by a lid; it is then rotated to the processing position, and after processing, it is rotated back to the waiting position. In the processing position, a set of three electrodes (45 MW) can be lowered into the melt to maintain or adjust the temperature.

The immediate objective of the work at the Ladle Furnace is, as in the ladle car, to remove oxygen from the charge. If this is not accomplished, the steel will be useless. For the purpose of deoxidation the formation of a reducing slag was prepared already when the ladle was readied for tapping. At the Ladle Furnace, this treatment is continued, by adding a mix of fluxes such as Al, Al$_2$O$_3$, CaO, and MgO as required, mixed according to the last EAF analysis before tapping and the aimed-at quality.

Deoxidation is also a precondition for desulfurization. The steel is, as a rule, contaminated with sulfur because of the presence of rubber, oil, and other organic materials in the scrap. If not removed, the sulfur will make the steel extremely brittle. However, the removal of sulfur cannot be accomplished to a sufficient degree in the electric arc furnaces for several reasons. First of all, for desulfurization to be effective the melt must be freed of oxygen. Furthermore, desulfurization requires a temperature above 1580 °C to happen, whereas depHosphorization requires a temperature below 1580 °C. Accordingly, in the EAFs the temperature of the melt is kept below 1580 °C until immediately before tapping. This was the primary reason for introducing the ladle furnace in the first place. Desulfurization is a prolonged chemical process and can most economically be carried out in the ladle, as opposed to the melting furnaces. To obtain steels low in sulfur, a ‘two-slag’ process based on ‘secondary steelmaking’ such as ladle metallurgy is essential. Desulfurization is accomplished by the formation of a reducing slag in the ladle, in that sulfur in the melt reacts with the calcium in the slag to produce CaS which then joins the slag floating on the top of the melt.

Deoxidation is also a precondition for alloying the steel. To ‘kill’ the steel and prevent nitrogen embrittlement, aluminum if often added from a wire feeder which runs a heavy aluminum wire through another refractory-covered lance and into the melt. This can be done at both positions. Most of the alloying elements
(carbon, lime, aluminum, ferromanganese, ferrosilicon) are dumped into the ladle from a battery of silos via a conveyer belt. When a high degree of accuracy is required, smaller amounts of carbon are added by means of a ‘carbon lance’, i.e., a refractory-covered steel tube through which carbon powder is injected into the melt. Finally, the ‘soft bubbling’ that was begun at the ladle car is continued and can be administered at both ladle furnace positions (Figure 10, right). All of these operations are controlled (initiated, executed, and registered) by means of the (interactive) process control system in the Ladle Furnace control room.

At regular intervals, the temperature of the melt is measured, and at approximately the same frequency samples of the melt and slag are taken and sent to the laboratory for analysis. When the operator is satisfied that the temperature and quality values stipulated by the relevant protocol in the plant’s catalogue of steel products has been achieved, a last sample is sent to the laboratory for analysis, for quality control purposes.

The Ladle Furnace control system also assists in some of the calculation work involved in making steel. Most importantly, in a matrix on the display, the system presents, for each alloying element, the target values, the latest test values, and (based on what has been added since tapping) the predicted composition of the charge, presuming, of course, that the tests are accurate and that all alloying elements will be dissolved in the melt.

At the final stage of the refinement process at the Ladle Furnace, when the ladle has been rotated back into the waiting position, calcium silicide (CaSi), enclosed in thin steel tubes, is fed into the liquid steel by a wire feeder. This may be done for various reasons. In the typical case of aluminum-killed steel, the aluminum oxide (Al₂O₃) that is the outcome of the deoxidation process, has a very high melting point; if it is not removed before casting, the Al₂O₃ will precipitate

![Figure 11. Left: Ladle en route to ‘The Tower’, as seen from the platform above the Ladle Furnace control room. Right: Casting platform: Steel teeming into tundish (DDS 1999a).](image-url)
in the molds and clog them. But by adding CaSi to the melt one obtains calcium aluminates that have a melting point lower than the melting point or ‘liquidus’ of steel, and as a result the problem of clogging the molds is neutralized. CaSi is also added at this stage when a very low sulfur content is required.

So, at the end of the ladle’s stay at the Ladle Furnace, the CaSi wire-feeder is rattling, after which the charge is ‘after-bubbling’ for about three minutes; when stirring has stopped, the ladle is picked up by the crane and moved to the casting platform.

2.1.5 ‘The tower’: casting

When the ladle arrives at the casting machines (indicated by ⊙ in Figure 3), it is by the crane placed upon another turntable device on an elevated platform in the hall, called ‘The Tower’ because of its prominence in the hall (Figure 11).

Steel is cast in one of two casting machines. At the billet caster, six strands measuring 142 × 142 mm square are cast simultaneously (Figure 12, left). By contrast, slabs are cast in one strand with a cross-section that measures from 150 × 1720 to 260 × 2070 mm, depending on the eventual product type (Figure 12, right).

In continuous casting, liquid steel is continuously teemed into a water-cooled vertical copper mold and, at the same time, the solidifying steel is continuously withdrawn at the other end. In fact, after it has left the mold, the slab or billet is far from solid: it has a conical core of liquid steel 6–8 m long, with a ‘skin’ of solidifying steel that is only 10 mm thick. To speed up the process, the solidifying steel passes through a ‘spray chamber’.

A critical control issue of continuous casting is that of matching the flow of liquid steel into the mold with the withdraw speed of the strand out of the mold. Controlling the pace at which casting proceeds and solidifying steel is withdrawn and the solidifying steel is cooling at the requisite rate is critical to ensure that a fine-grained
structure results from the crystallization process. The timing of this transformation process ultimately dictates the timing of all previous processes at the Steel Plant.

This control is, in part, made possible by the tundish, a small trough-shaped distributor lined with refractory that is placed over the mold and which receives the steel from a nozzle in the bottom of the ladle. The tundish thus provides a buffer after a fashion. However, the liquid steel in the tundish must be within a narrow temperature range just above the liquidus for the alloy in question. This imposes very strict demands on the performance of the Ladle Furnace in that the operator there must be able to hand over the refined steel within a very narrow window in terms of time and temperature. To prevent oxidation of the melt as it is teemed from the ladle into the tundish and is held there, the molten steel is covered with various shields and sometimes a ‘blanket’ of argon.

Finally, as the strand of solidifying steel is withdrawn from the caster, it is cut in different lengths according to requirements. The billets and slabs then move on for further processing at the Bar Mill and the Plate Mill, respectively, where the cast steel is subjected to a slow cooling process during which hydrogen captured in the steel dissipates.

After that, the slabs and billets are transferred from the Steel Plant to the other plants of the DDS to undergo subsequent thermomechanical treatments such as ‘hot rolling’ as well as heat treatment. The objectives of the subsequent processing are not only to give the product the required shape and dimensions but also to recrystallize the steel, typically in order to obtain a fine-grained microstructure.

2.2 Interdependencies

This is the overall picture: Dispersed over the large and motley environment that is the Steel Plant, in crane cockpits, in control rooms, at different locations on the plant floor, etc., the workers of the Steel Plant are engaged in various distinctively local tasks: moving scrap, lowering and lifting electrodes, melting scrap, taking samples, adding lime, blowing oxygen, removing slag, tapping from furnaces into ladles, adding fluxes, moving ladles, adjusting temperature, adding aluminum, blowing argon, adding CaSi, preparing a tundish for casting, tapping steel from ladles into a tundish, regulating the flow of melt into molds, repairing and preparing ladles for reuse, and so on.

And yet, the work activities at the different stations are intimately interdependent. There is, obviously, a rather linear dependence between work processes at the key stations (from the Scrap Yard, to the Electric Arc Furnaces, to the Ladle Car, to the Ladle Furnace, to Casting), in that the subsequent processes depend on the previous ones for their material, on its being handed over in due time and at the requisite quality and quantity, and at the required temperature. There is of course also an obverse dependence, in that operators in charge of the previous
processes need to be continually informed of the situation at of the subsequent stations.

However, before we move on, it should also be noted that the key processes also depend, in different ways, on a web of — so to speak, orthogonal — support activities: the laboratory producing a steady flow of analyses of the composition of melt; the renovation of ladles and tundishes; the cranes transporting baskets, empty and full ladles, slag pots, and tundishes; the supply of electrodes for heating and of oxygen, argon, nitrogen etc. for purging and bubbling; the supply of fluxes, and alloying elements from in-house delivery. And so forth. Further out in the support network, the whole operation on the shop floor depends on the ongoing work of maintenance, procurement, and planning, just like the entire Steel Plant operation depends on the steady supply of scrap and other raw materials, as well as electrical energy from external parties. We will by and large abstract from all of these support activities, as we focus on the key transformation processes, with those of the Ladle Furnace at the center of attention.

3 Distributed coordination

Overall, the work at the Steel Plant is process control work performed in control rooms. But the work organization is more complicated than that.

In certain respects, the work at the Steel Plant is comparable to work in ‘centers of coordination’ mentioned already in the Introduction (Sect. 1.4). The defining characteristic of this type of work organization is that workers located at the control center direct and align the activities of mobile or stationary workers at various locations outside of the control center. Or in the words of Suchman, work at such centers ‘is dedicated to the ongoing management of distributed activities in which one set of participants is charged with the timely provision of services to another’ (Suchman 1997, p. 114). In so far as the control rooms at the Steel Plant are centers from which the activities of mobile actors such as ‘hole man’, melter, assistant, crane drivers, maintenance workers, etc. are directed and coordinated, they can surely be characterized as centers of coordination. In other important respects, however, the role of control rooms at the Steel Plant differs from that of typical centers of coordination. First, what is being controlled by the Steel Plant control room operators are primarily the transformation processes themselves, not the movement of people or the transportation of materials by other actors. The primary concern of operators in the different control rooms at the Steel Plant is process control. Second, the typical communication and coordination pattern at centers of coordination is hierarchical, in as much as the center is a hub at which information is aggregated and collated and from which the distributed activities of mobile actors are coordinated. Although there is a local coordination hierarchy at the Steel Plant as well, with control rooms serving as bases for local mobile
workers, this is not characteristic of the coordination task of the process as a whole. There is no overarching center of coordination at the Steel Plant. Control of the overall web of transformation processes is genuinely distributed and thus rather exhibits a peer-to-peer pattern. In this regard, work at the Steel Plant might rather be compared to the coordinated effort of multiple air traffic control centers in maintaining an efficient and safe flow of flights across airspace.

Steelmaking is, basically, a series of controlled transformation processes (phase transitions, chemical reactions, recrystallization). As such it has defining characteristics in common with a large and ramified family of forms of work processes, from the cooking of food over a camp fire to the synthesis of organic compounds for pharmaceutical purposes. The task of workers with respect to transformation processes consists in monitoring the process and regulating the boundary conditions so as to enable the automatic process to run its course. What differentiates the various members of this category of work is, that some processes, such growing wheat, cooking and cuing food, or fermenting grape or barley juice, proceed spontaneously, without ongoing monitoring, and for a protracted period of time to produce acceptable results, as long as a broad band of conditions obtains, while others, such as nuclear power generation, chemical synthesis, and oil refinery are predicated on the maintenance of specific boundary conditions within a narrow range and require strict and continual control of boundary conditions. What is in any event shared by transformation processes is that they take their own sweet time. They may also be ‘time-critical’ in the sense that they proceed without human intervention, as long as the boundary conditions remain adequate and that they otherwise may result in quite undesirable and even catastrophic outcomes. Moreover, transformation processes, such as energy transformations, chemical reactions, and fermentation, and as opposed to fabrication processes like spinning, weaving, machining, sowing, or assembling, are inherently ‘invisible’ to the human eye, and can only be monitored indirectly by means of symptoms and other indicators, today by using all kinds of sensors and effectors and a host of computational and representational devices. The same applies to the Steel Plant. Metallurgical processes are automatic in that they occur on their own accord, spontaneously, when certain boundary conditions obtain; that is, when the required chemical elements and compounds are present and the temperature is sufficiently high, and provided the processes are allowed time to play out. In so far the work of the steelmakers is related to the work of operators in nuclear power plants (cf., e.g., Woods et al. 1987; Kasbi and Montmollin 1991; Rochlin and von Meier 1994; Bergman 1995; Rognin 1996; Vicente et al. 2001).

Again, however, there are interesting and illuminating differences. Typically, the work in the control rooms of, say, contemporary nuclear power plants is what Tom Sheridan has termed ‘supervisory control’ work (1976), that is, processes are coupled and controlled by an overriding computational control system. The transformation processes thus proceed without continual regulatory intervention.
by the operators. The operators are out of ‘the first-order loop’ of continual monitoring and regulating, and their role is rather that of controlling the computerized control system, i.e., supervising that the system at large functions appropriately, and then occasionally, when required, intervening. However, predicated on the solipsistic notion of (virtually unbounded) automatic control, the concept of ‘supervisory control’ is problematic. Computer control is of course inexorably bounded. The underlying computational model of the world is a ‘local and temporary closure’ (Gerson and Star 1986). There is, at any time, actual or potential occurrences to take into account in supervising the process, and there may, unavoidably, be situations where the system is ‘beyond its bounds’ (Roth and Woods 1989). Operators will therefore, so to speak, have to police the boundary. Even ‘supervisory control’ is work and ‘automatic control’ a technical complement to a practice.

Be that as it may, process control at the Steel Plant is a far cry from Tom Sheridan’s picture of ‘supervisory control’. First, at the Steel Plant, the computerized process control systems are insular, comprising an archipelago of local computer-based control systems. Computer control is restricted in scope to the control of temporally and spatially discrete operations: engaging the electrodes, adding fluxes and alloying elements, rotating the ladle furnace turntable, blowing argon, etc. Second, the control systems are interactive: it is the operator who decides to engage the electrodes (by pushing the appropriate buttons), when and for how long; and it is the operator who decides to add fluxes and alloying elements, when, what, and how much. In short, the operators at the Steel Plant are ‘in the loop’, although the control of the execution of some operations has been delegated to the computerized control systems. Third, while the control of the key processes is exercised by means of computerized control systems, some operations are straightforward manual operations (opening the tapping hole, taking samples of the melt, preparing a tundish for casting, etc.), or operating servo-mechanisms (driving cranes, releasing scrap into a furnace, etc.). Fourth, a crucial characteristic of work at the Steel Plant is that operators, for technical reasons that will be further developed as we move along, need relatively immediate access to unmediated and unfiltered visual and auditory inspection of their immediate field of work; for the Ladle Furnace operator, to monitor the intensity of argon bubbling, to assess the viscosity and color of the slag, to measure the temperature of the steel, take samples, repair minor faults, etc. The ensemble of steelworkers is therefore distributed across stations so that operators are physically close to the local processes they have to control. In sum, the transformation processes at the Steel Plant are not controlled from one central control room but from multiple local control rooms and by mobile workers on the floor as well. That is, and as noted already, the cooperative effort of producing steel is accomplished by a highly distributed work arrangement. The bottom-line is that, at the Steel
Plant, the continuity and integration of the constituent local processes are not automatically accomplished, not even semi-automatically (by an overall workflow system), but are the ongoing achievement of the distributed operators. The haunting picture of ‘wall-to-wall’ automation, where the ‘human factor’ has been marginalized, does not fit here.

It is here relevant to note, in passing, that work at the Steel Plant is distinctly different from the work described by Shoshana Zuboff in her famous study of computerization of process control in pulp fabrication (1988, Chapter 2). She reports that process operators, as part of the transition to computerized control of the process, were relocated to a central control room from which they could no longer directly monitor the state of the materials and equipment. They were left to rely entirely on data provided the computerized control system and therefore often felt at a loss. In the words of one operator, ‘it’s like driving down the highway with your lights out and someone else pushing the accelerator’ (p. 64). Operators at the Steel Plant, by contrast, are located in close proximity to the materials and equipment in their charge, and, accordingly, as will be demonstrated in the following, they are able to directly monitor and inspect the evolving local state of things.

The cooperative effort at the Steel plant is extremely distributed for a process control operation. There is no global space of continual communication at the Steel Plant. This is in contrast to a conversation or a meeting, where the interlocutors are (in principle) presumed to know equally well what has been said and done in the course of the conversation, or for that matter work at a control center or on the bridge of a ship, where workers are able monitor the conduct of one another. At the Steel Plant, what takes place at a particular location is not known at any other location, and to make it known requires work.

The only continually updated representations of the state of affairs in the overall process that is available to the distributed actors are the laboratory analysis reports that are broadcast and displayed in each control room, based on analyses of the samples submitted from the various stations, from the Electric Arc Furnaces to Casting and Adjustment. However, while the system presents an analysis of the composition of individual charges, the order in which individual analysis results are presented is determined by the order in which test samples are received and processed at the laboratory, and as such arbitrary. Operators have no way of controlling the presentation of test results (e.g., by retaining, selecting, etc.). Instead, the results appear at the bottom of the screen and then scroll by as new test results are published, very much like share prices are paraded on screens in stock exchanges. Nonetheless, from the laboratory analysis reports the Ladle Furnace operator can in principle inspect the quality and hence readiness of the charges being melted and refined in the furnaces. In a similar fashion the Ladle Furnace operator can calculate the point in time when the next charge is due from the casting progress counter on the wall.
The radio channel of the crane drivers does provide a global communication space of sorts, of course, in so far as all crane drivers and process operators can overhear exchanges among crane drivers and between a crane driver and an operator. The channel is not used by process operators for conversation among themselves, however, and would probably be clogged if it was. For most practical purposes, that is, the radio channel is a sideshow.

Finally, the Ladle Furnace operator as well as the other operators do engage in abrupt intercom exchanges and now and then even conversations with other operators and with mobile actors in order to transform the production plan into an operational schedule and in turn transform the schedule into a continuous process. The short verbal exchanges that do take place, albeit intermittently, are all quite local, i.e., point-to-point: EAF operator ↔ crane driver, EAF operator ↔ 'hole man', EAF operator ↔ ladle preparation station, Ladle Furnace operator ↔ crane driver, Ladle Furnace operator ↔ EAF operator, Ladle Furnace operator ↔ Casting operator, etc. (Examples of these discursive interactions will be described in Sect. 6).

4 The complexities of making steel

Distributed over the plant, the workers are deeply interdependent in their work; thus, ongoing coordination and alignment of the distributed activities are crucial; it is paradigmatic cooperative work (Schmidt 1990, 1994). However, the workers at the different stations face a spectrum of very specific complexities that raise specific challenges to their effort to coordinate and align their distributed activities. This is where our analysis must begin (Schmidt 2002b): What are the sources of uncertainty, variation, and contingency of making steel and for doing so in a reliable and orderly manner?

4.1 Petty concerns

It is a critical source of the complexity of steelmaking that minute differences in the composition of steel have enormous and even incongruous effects on the macroscopic properties of steel.\(^{20}\)

Steel, as we now know, is a carbon alloy of iron. Furthermore, different carbon contents have very different consequences for the properties of the steel. Increasing the carbon content yields steel of increasing hardness and tensile strength, but also of decreasing ductility and increasing brittleness. But iron also forms alloys with most of the metallic elements, such as manganese, chromium, nickel, and vanadium, just as iron also forms compounds with most of the non-metallic

\(^{20}\) For an overview of the elements of concern to the workers at the Steel Plant, see ‘Appendix II: Main alloying elements and their effects on steel properties’.
elements, in particular — in addition to carbon — silicon, oxygen, nitrogen, and sulfur (not to mention phosphorous, which in any event is considered a pollutant).

The fact that the presence of even minute amounts of foreign elements and compounds has radically different effects on the properties of steel, is the source of the immense and diverse usefulness of steel, but is also, by the same token, the major reason why contemporary steelmakers are greatly concerned with the composition of the steel. It is therefore also an underlying but recurrent theme in the Steel Plant’s internal tutorial materials. The root of the concern, it is explained, is to be found at the atomic level.

Metallurgists have known for centuries that iron and steel have a granular structure (e.g., Biringuccio 1540). This was never a secret, for the granular structure can be seen at the fracture surface when a bar of iron or steel is broken. What we now know, however, is that iron, like all metals in their solid state, has a crystalline structure. When liquid iron cools and solidifies, crystals form and grow, like ice crystals on a window pane. The growth of the crystals stops when the boundaries of individual crystals meet. Metallurgists have called these bounded crystals ‘grains’.

Although unknown until recently, this crystalline structure of steel was the foundation of the revered techniques of steelmaking from the very beginning: the techniques of thermomechanical treatment of iron in which solid iron is taken through a series of, typically repeated, processes of heating and cooling of various duration, sometimes quick, in water or oil or some other liquid, sometimes gradually, in the air. These techniques are not practiced at the Steel Plant but

Figure 13. Phases of iron.
(Source: Illustration from the Steel Plant’s internal tutoring materials. Legend translated by the present author).
they are the primary tasks of the other plants at the DDS site that receive the solid steel from the Steel Plant for further processing and finishing. Meeting the requirements of these customers is the *raison d’être* of the Steel Plant. Explanations of the basis of their requirements therefore features prominently in the metallurgical education of the workers at the Steel Plant. A short outline of theory of the nature of steel is therefore part of this ethnography.

The gist of it is this. Let us begin with the simple structure, namely, that of iron. At the atomic level, iron crystals assume three distinctly different lattice structures, depending on the temperature (Figure 13). In the range from room temperature to 911 °C, iron atoms are arrayed in a regular cubic lattice, with atoms at the corners of the cube and one atom at the center. This lattice structure — the ‘α’ structure or ‘phase’ — is called ‘body-centered cubic’. Between 911 °C and 1392 °C, another stable lattice structure emerges, the ‘γ’ phase. The lattice structure of ‘γ iron’ is also cubic, but atoms are here placed at the center of each face of the cube as well as at its corners; that is, it is ‘face-centered cubic’. Between 1392 °C and 1538 °C, the stable structure again assumes the body-centered form, now called ‘δ’. Finally, at 1538 °C, iron melts and transitions to the ‘liquid phase’. In other words, as iron is heated or cooled off, it goes through these regions of stability, or ‘phases’, and at each transition point below liquidus it is re-crystallized.

In steel, i.e., in carbon alloys of iron, however, the phase transitions are much more complex, as they not only depend on temperature but also composition. As

![Iron-carbon phase diagram](image.png)
noted already, iron will be liquid at 1538 °C and above, and in this liquid carbon will be dissolved just as a pinch of salt is dissolved in a pot of hot water. The point is that carbon can be dissolved in iron, not only in liquid iron, but can remain dissolved in solidified iron (above 400 °C), in a state called ‘solid solution’. 21

To handle the complexity of the ‘iron-carbon system’, metallurgists use the ‘iron-carbon phase diagram’ (Figure 14). It represents, in the form of a coordinate system, the different states, or ‘phases’, of ‘thermodynamic equilibrium’ in the ‘iron-carbon system’ according to temperature and composition. In the words of John Clerk Maxwell’s description of the function of such diagrams, the ‘geometrical relations between the parts of the figure help us to understand relations between other objects’. In addition, the iron-carbon phase diagram also serves purposes of measurement in a way similar to a city map or a construction plan: ‘The plans and designs drawn by architects and engineers are used to determine the value of certain real magnitudes by measuring certain distances on the diagram’ (Maxwell 1877, p. 149). In other words, it is a graphical calculus summarizing a mountain of practical and experimental data underpinned by solid-state physics and thermodynamic theory.

The steel-carbon phase diagram shows, among many other things, that pure iron will only become liquid (L) at 1538 °C, while a 4.30% iron-carbon alloy (‘cast iron’) will become liquid already at 1147 °C, the lowest possible melting point for an iron-carbon alloy. That is, the melting point decreases with increasing carbon content (until the ‘eutectic’ point at 4.30% C). This phenomenon of course also occurs when table salt (NaCl) is added to water or ice. That is, it shows that the melting point for cast iron (from about 2% C and higher) is significantly lower than for the steel range. Thus, if you follow a vertical line from a point indicating, say, 0.76% C on the horizontal axis and move vertically through the regions of increasing temperature, you move through different phases of the iron-carbon alloy: from the ‘α’ or ‘ferrite’ phase assumed by steel at room temperature (where it coexists with the carbon-iron compound ‘cementite’ or Fe₃C)

21 A solid solution should not be confused with a compound. Iron and carbon atoms do not bond to form molecules; instead, in solid solution carbon atoms are trapped in iron’s lattice structure.
to the ‘γ’ or ‘austenite’ phase, at 727 °C, and at even higher temperatures, at about 1450 °C, the steel begins to turn liquid. On the way down the temperature scale, the whole sequence is of course repeated in the inverse order.

When the temperature drops and the steel solidifies and slowly cools off, the iron atoms will be arrayed in the lattice arrangement, but now the carbon atoms are squeezed-in between the iron atoms (Figure 15). Carbon is now in ‘solid solution’. This is possible because carbon atoms are much smaller than iron atoms and therefore can be lodged in the cavities between the iron atoms. That is, as the steel solidifies and cools, carbon atoms do not substitute for (or replace) iron atoms in the lattice but are ‘lodged interstitially’ in the lattice. The presence of foreign atoms in the lattice causes distortions in the lattice, which in turn makes the lattice harder (Figure 16). When the temperature drops to below the austenite borderline, the iron atoms rearrange to a lattice structure in which there is less space for carbon to be lodged in the cavities, namely, the ‘α’ or ‘ferrite’ phase or, for iron with more than 0.022% C, ‘ferrite’ and ‘cementite’ (Fe3C). However, the carbon atoms do not immediately ‘come out of solution’ but will migrate towards areas where the temperature remains high and where the lattice remain in an arrangement (‘γ’ or ‘austenite’) that still offers room to accommodate them. Consequently, the concentration of carbon increases in these areas. All solid steels containing 0.022% to 0.76% carbon will undergo the same transformations when heated to above critical temperature and then cooled again.

Whereas carbon is an interstitial solute, atoms of alloying elements such as manganese, chromium, nickel, molybdenum, and vanadium substitute for atoms of iron in the ferrite lattice in a (substitutional) solid solution (cf. Figure 15). But again, since an atom of an alloying element will differ from the host in size and electronic structure, the host lattice is distorted in the immediate vicinity of the

Figure 16. Distortions of the iron lattice due to the presence of foreign atoms in solid solution: as substitution (a), and interstitial (b). (Source: Illustration from the Steel Plant’s internal tutoring materials).
alien atom, causing internal tensions to the lattice, which in turn makes the steel harder (cf. Figure 16).

For steelmakers, the practical implications of the sensitivity of steel are these. First of all, accuracy is of paramount importance. At the Steel Plant the composition of steel is measured in fractions of a percent. For instance, for the slab type called ‘S-23’ the carbon content must be at least 0.122% and maximum 0.140%; the ‘ideal’ carbon content is 0.135%. This means that the Ladle Furnace operator has to achieve carbon content within a margin of ± 0.009% (or ± 9 × 10⁻⁵).

Furthermore, significant complexity arises from the effect of the interactions between alloying elements for the resulting properties of the steel. Specifying a particular steel quality is a trade-off decision. The issue of weldability is quite instructive in this regard. All steels for construction purposes (e.g., ship building) must be suitable for welding (without special precautions such as preceding and subsequent heat treatment). The problem here is that steels that harden well when heated to the austenite region and then cooled rapidly, will do exactly that when welded — and thus embrittle. Because the general effect of adding carbon to iron is to increase ‘hardenability’, steel with a high carbon content is not suitable for construction purposes. But on the other hand, low-carbon steels are deficient in tensile strength. The obvious way out is to opt for alloying elements that increase tensile strength, such as chromium, vanadium, molybdenum, nickel, manganese, etc. However, these alloying elements also contribute to the hardenability of steel, albeit less radically. These elements can therefore be used as substitutes for carbon, but their effect on hardenability has to be very carefully controlled.

If the effect of one part carbon (C) on hardenability is 1, the effect of one part manganese (Mn) is 1/6; the effect of chromium, vanadium and molybdenum 1/5, and so on. The combined effect of all of these alloying elements is called the ‘carbon equivalent’ and is expressed in this general formula:

\[ C_{eq} = C + \frac{Mn}{6} + \frac{(Cr + V + Mo)}{5} + \frac{(Cu + Ni)}{15} \]

In the production of structural steel, the carbon equivalent has to be carefully controlled so as to control the hardness and hardenability of the steel, and a key task for the operators is therefore to monitor for the value of the carbon equivalent. In general, carbon should be held below 0.25% and Ceq below 0.50%. The carbon equivalent formula therefore plays a central role in the ongoing work of the Ladle Furnace operator.

By adding, say, niobium to the steel, one obtains a steel of high tensile strength that is also quite suitable for welding as well. Like aluminum, niobium is a micro-alloying element, that is, an element that is added in extremely small quantities and achieves its effect by reacting with other elements in the steel, in the case of niobium with nitrogen and carbon. The resultant compound restrains grain growth at high temperatures and facilitates a steel with extremely high yield strength and (after ‘normalization’)
tensile strength and ductility and which can be welded as well. However, since a niobium content of more than 0.03% causes loss of ductility, the niobium content must be controlled extremely tightly in turn.

Altogether, micro-alloying elements must be controlled far more accurately than carbon. When, for example, boron is added, which is done to achieve a steel with high tensile strength that is also suitable for both hardening and welding, the boron content should not exceed 0.003%. However, since boron reacts with atmospheric oxygen and nitrogen and therefore will quickly vanish from the melt in the course of the production process, small amounts of aluminum and titanium will be added to shield the boron.

In short, a critical concern of all actors involved in the production of steel is to delicately balance the composition of the particular alloy quality.

For the same reasons, actors must take great care to control impurities in the steel. A waste product, scrap iron by nature contains various non-ferrous materials such as sand and rubber which in turn leaves impurities in the melt in the form of silicon, phosphorus, and sulfur. These impurities may have very negative effects even in very small quantities (from 0.005% to 0.02%, in the case of sulfur). A major concern of steel plant operators is therefore to remove these impurities, especially phosphorus and sulfur, from the steel in a controlled manner in the course of the process.

At the ‘higher’ level of grain formation, the presence of foreign elements and compounds may also prevent or inhibit grain growth. Here aluminum plays an important role at the Steel Plant. A major drawback with electric arc furnace steel production is that the molten iron is exposed to atmospheric air in the area around the electrodes. As a result, nitrogen becomes dissolved in the melt, and when the steel has eventually solidified, the nitrogen is still there, as free atoms. These will migrate within the crystal structure and assemble at grain boundaries and dislocations which will then become sources of fractures. However, if small amounts of aluminum (or titanium) are added to the steel before casting, nitrides (e.g., AlN₄) will form (when the steel is normalized later in the process), which in turn will ‘pin grain boundaries’ and inhibit grain growth. The result is finely grained steel.

In sum, then, the immense range of incongruous properties of different steels is a manifestation of the combined effect of the readiness with which iron forms alloys with carbon and other elements; the responsiveness of iron to even minute amounts of foreign elements; the sensitivity of the properties of carbon alloys of iron to heat treatment; and the radical structural effects that can be achieved by subjecting carbon steel to mechanical working. Because of the contradictory properties steel can acquire and the extraordinary sensitivity of these properties to the presence of very small amounts of alloying elements and impurities in the steel, steelmaking requires delicate handling of a range of quite tricky trade-offs. Consequently, the operators have to very carefully
control the chemical composition and physical morphology of the steel as well as the timing of the processes.

It may be heavy industry, but it requires precision and finesse.

4.2 Uncertainties

Steel production is characterized by inherent uncertainties. The refinement and alloying processes in particular consist in a complex of concurrent and interacting chemical reactions, kinetic processes of diffusion, mechanical processes of purging, etc. They are transformation processes in the strongest sense of the word.

Since chemical reactions of course are invisible to the naked eye (they occur at the molecular level), steel workers, in controlling the processes involved in purging melt of impurities and ensuring the desired composition and homogeneity, depend on a host of indicators such as measurements of temperature and chemical composition.

However, in the EAFs, elements such as carbon, phosphorous, copper, tin, etc. are unevenly distributed in the melt. Obtained from spot-measurements of the melt, by means of samples, the available data of the state of the melt and slag are at best approximations and may be misleading. Because of this fundamental uncertainty, small and not so small surprises are part and parcel of steelmaking. For example, the analysis report from the last sample taken from a charge before it was tapped may misrepresent the composition of the charge received by the Ladle Furnace, because typically oxygen will be blown into the melt also after the last sample has been taken and this may have altered the carbon content considerably. It may take some time until the mistake is realized, and regulatory measures taken in the meantime may even have made matters worse.

Similarly, Ladle Furnace operators are regularly dealing with wicked problems such as: Is the carbon that has been added to the charge, but does not show up in the analysis on the control display, still in there, in the slag, or has it been burnt off? Should we add more carbon, or will that make matters worse? Likewise, if for some reason a charge has been tapped at a temperature lower than presumed or the ladle was not as hot as planned or the ‘skull’ was thicker than thought, the removal of sulfur from the charge (one of the purposes of ‘soft bubbling’ the charge on the ladle car) does not work effectively, and as a result the refinement at the Ladle Furnace will take longer. This, in turn, may of course affect the continuity of the overall process.

Therefore, as it is expressed in a tutorial note written by a shop steward at the time the new ladle furnace was installed and put to work:

’slag inspection is actually the real control ensuring that the ladle furnace process is proceeding as intended – and the iron rod you use for taking slag samples is the most noble measurement instrument at the ladle furnace. Everything else – electrodes, transformers, weighing-out silos, conveyor belts, water-cooled lids, wire feeders and our fancy
computer, are really tools developed in order to create and maintain the slag that is necessary for the refinement process.’ (‘Om slagge – som vi ser den’ (‘On slag – as we see it’), undated paper in Ladle Furnace instruction binder, written c. 1986).  

The shop steward goes on to explain that slag inspection comes down to astute perception of the slag. First, he points out, the main element in the slag is lime and lime is a compound of calcium and oxygen, Ca and O.

‘What we want to achieve is that some of this Ca gives up its oxygen (O) and reacts with the sulfur in the steel, that is, becomes CaS. To make that chemical process happen, the first requirement is that the mass of slag has been melted is liquid, but lime is not all that susceptible to melting – lime has a melting point above 2200°C, and if we get up to these temperatures, we will also melt the fire-resistant refractory materials in the ladle, in as much as the stone largely consists of lime. What we do instead is to lower the melting point by adding either sand (SiO$_2$) or fluor spar (CaF$_2$) into the slag. If we at the first slag check observes that the slag is not liquid, we either have to heat it further or add more sand or fluor spar.

When we have achieved a liquid slag, the next problem is to remove all the free oxygen from the slag.’

This, he explains, is done by adding ‘alumix’ to the slag:

‘Aluminum is a good at binding oxygen, and it does not merely bind itself to the free oxygen in manganese oxides and ferro oxides in the slag. By taking samples from the slag, we can monitor how far this process has come. When we see a black slag, we know that it is the manganese oxides and ferro oxides that gives it that color, and we have to add alumix, until we see a bright (preferably completely white) slag. Only then can we be sure that there may be a surplus of aluminum in the slag, not bound to oxygen; for even if aluminum is much bet-

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22 I quote the shop steward’s note at length here, not only because it explains the process quite well, but also because it describes a key aspect of the operators’ practice and exemplifies the nature and extent of the technical knowledge of the operators: They understand and account for their work in terms based on scientific metallurgy. — In a memo written by an engineer at the same time, the same issue is expressed as follows: ‘In order to control whether the slag is in fact liquid and deoxidized, we only have our eyes.’ Similarly, ‘we […] cannot know for certain what the slag can give in the form of manganese.’ — (‘Ske-ovn’ (‘Ladle Furnace’), internal memo dated 7 January 1986, authored by HEN.).

23 ‘Alumix’ is a standard commercial granulate consisting of 40% Al$_2$O$_3$ og 30% Al.
The point here is that the work of the Ladle Furnace operator depends critically on direct inspection of the slag, its color and viscosity. The Ladle Furnace operator will, for example, on a regular basis turn to the window to inspect the slag floating on top of the charge in the waiting position. If the slag is black, she knows that it contains a large amount of ferro oxides and manganese oxides and that she has to add aluminum until it is all white. She may not even have to turn and look. Often, when a charge is being heated in the ladle furnace, a very characteristic ‘rumbling’ sound can be heard, accompanied by a shower of sparks from the ladle. ‘It’s a little on the thick side, so it’s just growling a little’, is the explanation given to me. That is, the growl and sparks is taken to indicate that the slag is more than ordinarily viscous.

Once or twice for every charge, the Ladle Furnace operator will put on her helmet and leave the control room to inspect the state of the charge more directly. She has many reasons to do so. As noted above, she needs to see the color and viscosity of the slag to have a better idea of its composition. But she may also want to inspect the conditions for adding carbon to the charge: Does the bubbling of argon create a clearly demarcated ‘bubble spot’ in the slag, that is, a spot of exposed melt? If the slag is ‘thick’, there will be a ‘bubble spot’ surrounded by slag forming a wall (Figure 10, right). If carbon is to be added to this charge by means of the conveyer, the carbon can be dumped here where it will enter the melt, not the slag. However, if the carbon lance is to be used instead, the slag should be ‘thin’.

Nonetheless, in spite of her ventures outside of the control room, her assistant, who is regularly working on the platform outside of the control room (e.g., measuring temperature and taking samples), is her ‘eyes and ears’. Referring to her assistant, she at some time explained, in an aside remark during operations:

‘At the same time as he takes a sample, he’ll look at the slag that comes up on the test rod. If there just a pearl or two, he’ll see it instantaneously: is it glassy, or is it lime, or is it white, or is it black? Or what is it? You’ll notice that immediately.’

In short, without easy access to perceiving the slag, operators would be severely handicapped.

The spatial distribution of the ensemble across stations has the advantage that it brings operators in close proximity of the processes they are managing. The significant downside of this is, of course, that workers at different stations cannot see each other, nor have they have significant direct visual means of monitoring the state of affairs at the other stations.
4.3 Routine variations

The coordination of the distributed and yet strongly interdependent activities of the steelmakers is further complicated by the variability of these interdependencies.

First of all, the duration of the refinement and alloying processes at the Ladle Furnace varies with the different steel qualities. The Ladle Furnace operator will have to allow for variable refinement times in scheduling her work to match the foreseen casting rate for a casting sequence.

Second, the speed of the casting process is far from uniform. First, the ladle with the first charge in a sequence is emptied faster than the subsequent ones, because the first 30 tons or so fill the tundish before teeming into the mold.

Third, the timing of casting is very different from slabs to billets. When casting slabs, the speed of the process is determined by the dimension of the slabs. The larger the area of the cross-section of the product, the larger the cross-section of the mold, and the faster the ladle is emptied. The duration per charge of the casting of slabs varies from 30 min, for the largest slab dimensions (260 × 2070 mm), to 45 min. When beginning a series of charges for the largest slab dimensions, where they will required to meet to a cycle frequency of 30 min, Ladle Furnace operators will strive to have a small stock of three charges (or 300 tons) tapped before casting is commenced; they also prefer to have the fourth charge ‘on the second basket’, i.e., the fourth charge must be 15–20 min from tapping. This means that the Ladle Furnace operators must have one charge ready for casting, in the waiting position, one charge under treatment, and one charge waiting on the Ladle Car. With the smaller slab dimensions, the temporal constraints are not as severe. In these cases, two charges must have been tapped and the third charge must be ‘on the second basket’ before casting is initiated.

Fourth, as far as billet casting is concerned, a casting sequence only involves two to four charges. However, refinement of steel for billets takes longer since these products normally must not contain aluminum; instead, the steel is ‘killed’ by adding silicon, but this takes longer than trimming with aluminum. Thus, before billet casting is started, there should be two charges at the Ladle Furnace, and the second charge should be about ready for casting (i.e., the lab analysis report should have arrived first). Although the casting speed does not vary, as billets have the same cross-section, the number of molds in operation may vary. Normally six molds are in operation simultaneously, but one or more molds may be out of operation, or fall out, and in that case, casting will take longer, and the preceding processes will have to adjust their pace accordingly and, as noted above, hand over steel at a higher temperature than otherwise required.

On top of all that, there are variations in temperature and composition that operators must take into account and control. Because the casting equipment absorbs energy from the melt, the first charge of a casting process must have a higher temperature than the subsequent charges of the same run. Thus, in the case of slabs, the first charge must be 45 °C above liquidus, as opposed to the
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subsequent charges that are to be 40 °C above. This is of course predictable and is standard procedure. However, there are the contingent variations where temperature and composition deviate from the aimed-for optimum that cannot be dealt with because of the temporal requirements from continuous casting. Thus, the composition of any given charge will typically deviate from the optimum value within the very narrow margins allowed for composition (e.g., for S-23, the carbon content margin is ± 0.009%). Such deviations must be taken into account in the treatment of the following charges in the same series so as to ensure a sufficient degree of homogeneity of the eventual solid steel. Thus, the average composition of the remaining charges within the same casting sequence must deviate to same side as the first charge. These are what could be called second-order variations. Deviations from optimal temperature must be taken into account in the same way. And again, if the temperature of the first charge was not quite nominal (that is, differs from the nominal, say, 45 °C above liquidus), the subsequent charges must again deviate to the same side. In the case of billets, on the other hand, even more variation may be on the agenda. The surplus temperature of the first charge in a billet series varies according to the specific alloy under production, whereas that of the subsequent charges must be 50 °C above liquidus. However, if only four or fewer strands are being cast, the total cross-section of the molds is smaller and the process therefore slower; consequently, the temperature has to be higher than otherwise.

Finally, there are the contingencies arising from equipment failures and local breakdowns. The metallurgical processes of steel production are violent in terms of extreme temperatures (1500–1620 °C), rapid chemical reactions, vibrations and shocks, high pressure, sparks and leaks of molten steel and slag, strong electromagnetic fields, electrical flashovers, and dirt and dust everywhere. The resulting wear and tear on equipment is atrocious. All stations in the plant thus routinely experience disturbances due to failing equipment. Faulty equipment is reported virtually every day in the operators’ report book.

Although operators and maintenance workers alike will state, in colorful vernacular Danish, that preemptive maintenance is something unheard of (‘preemptive maintenance, that’s a town in Russia!’), the explanation of the observable state of the plant should not necessarily be found in negligence on part of management or maintenance workers. A regular preemptive maintenance plan is followed. Every Wednesday, on the morning shift, production is stopped for major maintenance work. The EAFs are cleaned out, hatches are repaired, etc.

However, since unscheduled maintenance stops will halt the entire process, they are avoided, if at all possible, or postponed until the next scheduled stop, unless, of course, the malfunction poses a hazard to people, the plant, or the environment. For the same reason, in the case of such stoppages due to breakdowns, urgent local repair work is performed under time-pressure and not always done well: ‘There isn’t much time when production is running’ I am told. ‘You can tighten a bolt or
two, but not much more than that.’ But when accidental stoppages do occur, the opportunity is immediately seized upon to do minor maintenance tasks.

4.4 A rigorous temporal order

‘Cooperative work mediated by the technical facility differs fundamentally from team-based cooperative work in that the technical facility imposes a rigorous temporal order on the work.’

Popitz et al. (1957, p. 60)

At the Steel Plant, the constitutive processes of steelmaking are physically decoupled. Scrap is collected and moved in baskets by crane and then melted in two steps, basket for basket; the molten steel is tapped into ladles, charge by charge; the charges are, charge by charge, refined and alloyed at the Ladle Furnace, and from there moved to Casting. That is, the overall process has the basic characteristics of a series of batch processes.

However, a continuous casting sequence may last several hours, for some slab products up to five hours, during which time the preceding processes must deliver steel at the right temperature and quality and at the right time. Casting can be interrupted, of course, but interrupting the casting process is costly. If the process is interrupted, the tundish must be replaced by another which then must be heated, a process that lasts 1:30 hours for billets and 2:15 hours for slabs. In the meantime, the plant stands still while the meter is running, ticking at a rate of DKK 5 million per day.

In most other forms of batch-oriented production (e.g., manufacturing), one can stockpile intermediate products (parts and subassemblies) to provide buffer inventories between processes so as to ensure that down-line processes are fed continuously. This is not possible here. The plant only has capacity for holding and maintaining three ladles with liquid steel. But not only that. Liquid steel at about 1600 °C is a volatile and aggressive substance; chemical reactions happen very rapidly. At this temperature the refractory walls of the ladle are ‘eaten’. A ladle can hold steel for about six hours, after which it is no longer safe and may spring a leak. This may in fact happen earlier if the ladle for some reason has a hidden defect. This happened twice in the field work period. In one of these instances, 10–15 tons of melt poured out of the side of the ladle, covering the wheels and tracks of the ladle furnace turntable. Everything was welded together and the recovery efforts lasted an entire shift. The likelihood of such occurrences of course increases when melt is kept for longer periods. Furthermore, at about 1600 °C the composition of the steel is not stable: constituents such as carbon are oxidized, and atmospheric gases such as oxygen, hydrogen, and nitrogen are dissolved in the steel. Finally, once the steel has been tapped, the temperature of the melt drops at a regular pace: 0.25 °C per minute (and 1 °C per minute during
argon stirring). For instance, a charge that had been waiting on the ladle car for 1:20 hours had lost 120 °C. The melt can be reheated at the Ladle Furnace, of course, but reheating the melt to maintain the temperature adds carbon to the melt (from the graphite electrodes).

That is, the rigorous temporal order is exacerbated by the very strict tolerances required of quality steel and the ensuing demands on the production process. Or in the word of an engineer, ‘if one only had plenty of time, one could make the most perfect steel.’ In other words, due to the constraints and concerns of the casting process, work at the preceding processes — melting, refinement, and alloying — is subjected to a ‘rigorous temporal order’:

‘Cooperative work mediated by the technical facility differs fundamentally from team-based cooperative work in that the technical facility imposes a rigorous temporal order on the work.’ [In such a setting] ‘the work activities are subjected to a temporal order determined by the intrinsic time [Eigenzeit] of the technical system, the prescribed succession of operations and the necessity of maintaining the continuity of the process’ (Popitz et al. 1957, pp. 60 f.).

Consequently, because the processes at the different stations are de-coupled, it is for the workers at the different stations to coordinate and align their activities at the different stations in such a way that the discrete processes are integrated and the process as a whole is given the character of a continuous process. That is, for the workers tasked with managing the processes feeding melt to continuous casting (melting, refinement, alloying), it is the temporal requirements of the casting process that sets the pace. The paramount concern of the cooperative effort beginning in the scrap yard and ending as solidifying billets and slabs leave the molds and roll away to cool off is to accomplish continuity across discrete processes at spatially dispersed stations. The Ladle Furnace is the critical nexus in this overall process. Since its primary role is to achieve tight control of the metallurgical processes so that liquid steel of the requisite quality is handed over to Casting within the small window in the timing of the entire trajectory, the Ladle Furnace operator is, so to speak, the lead player of the ensemble.

In sum, the entire trajectory of work — from the time where a basket of scrap is collected in the scrap yard to the solidifying steel is being withdrawn from the mold — is time-critical. Achieving a rigorous temporal order is essential. Striving to achieve that, however, workers at the different workstations are faced with local uncertainties, variations, and contingencies that threaten to upend the temporal order. The different processes vary in terms of duration, their state can only be determined by indirect means, with an element of uncertainty, and may harbor surprises. If not contained, the resulting local delays will propagate down the chain and may cause further and perhaps irreparable delays, just as delays
downstream, in casting, may force workers upstream to postpone, if possible, the charges already waiting or under treatment, and suspend handovers.

5 Coordinative practices of the third order: providing the base of technical knowledge

This is our question: How do the workers at the Steel Plant at all manage to coordinate their distributed activities under these conditions? How do they, dispersed across separate shops and control rooms and focusing on local process, manage to achieve a practically continuous flow of steel for hours? As coordinative practices are complex, this is a question the answer to which has manifold determinations. For the sake of simplicity, I will approach the question in several steps, not unlike the process of peeling an onion, layer by layer. First, I will outline the technological and scientific foundation upon which the operation at the Steel Plant is predicated. I will do that by attempting to reconstruct the development of steelmaking technologies from the handicraft traditions of the ancients to the revolution in scientific metallurgy in the twentieth century that have reconstituted steelmaking theory and practice. I will then move on to describe the preparatory steps that are taken on a day-to-day basis, to the occasions of discursive coordination and synchronization, and, eventually, to the ongoing coordinative activities, in the midst of it.

5.1 Paradigms of steelmaking

‘By skill with fire and fluxes is made that kind of iron from which steel is made’.
Agricola, *De re metallica* (1556, p. 417)

‘Steel is made by dissolving carbon into iron’

Steelmaking techniques and practices have undergone radical changes over the centuries and are now fundamentally different from the techniques and practices of preindustrial steelmakers and even from those of steelmakers of the early twentieth century.

Until the Industrial Revolution, steel products were made manually, laboriously hammered into shape, piece by piece. For millennia, no steel product was made by casting liquid steel into a mold. It simply was not possible for steelmakers to reach the high temperatures required to melt steel for casting, nor did they have the ceramic vessels that could hold liquid steel. Only towards the end of the eighteenth century did manufacturers begin to be able to produce liquid steel, in crucibles, for casting, and only towards the end of the nineteenth century did it become technically feasible to produce steel by casting on a mass scale. And in fact, it was only
in the course of the twentieth century, more accurately not until around 1960, that steel-making technology was put on a rigorous scientific footing. Constituted by the application of scientific metallurgy of steel, contemporary steelmaking practices are of a different kind from those of traditional steelmaking.

First, the very concept of ‘steel’, as used today, is of a different category than the traditional concept. The contemporary concept of ‘steel’ is expressed in the iron-carbon phase diagram (Figure 14). It is predicated on the insights of contemporary scientific metallurgy and is defined in terms of, primarily, chemical composition (from 0.03% to 2.1% carbon), but also the microstructure of the metal (granularity, dislocations). Steel is today conceived of as a polymorphous material the properties and internal structure of which vary with the content of carbon (and other alloying elements) and, in a quite intricate manner, with its distribution in solid steel.

This makes the contemporary concept of ‘steel’ profoundly different from the concept of ‘steel’ that was used in the course of the long history of making iron and steel. From the beginning of the production of iron some 3500 years ago, the term ‘steel’ was used of a mixed family of iron products of different makeup, resulting from the application of quite different techniques, but which nonetheless had in common that they, in different ways, were both hard and strong, in contrast to the ductility of ‘wrought iron’ and the brittleness of ‘cast iron’. That is, steel was defined in terms of a variety of properties. What was considered ‘steel’ was based on the utility of an assortment of iron products for a range of practical pursuits such as cutting, piercing, digging. It was a pragmatically defined concept, a family-resemblance concept.

The concept of ‘steel’ was a family-resemblance concept for the simple reason that steelmakers could not identify the defining chemical and microstructural characteristics of steel: its being a carbon alloy of iron.

The notion of alloys was of course well known to ancient metallurgists who knew, for example, that bronze is an alloy made of copper and tin (c. 88/12%). These elements were well-known and were produced and traded in their relatively pure state (as standard-sized ingots). However, with regard to steel, nothing in its production and appearance suggested that it was indeed also an alloy. It was made from iron, and no other elements were apparently involved. Only about 250 years ago was it realized that carbon is indeed an element and moreover that ‘steel’ is a family of carbon alloys of iron.

24 For general accounts of the history of steel technology, see, for instance, the works by Mehl (1948), Wertime (1962), Smith (1981), Tylecote (1987, 1992), Rostoker and Bronson (1990), Sherby and Wadsworth (2001), Craddock and Lang (2003), Goody (2012), and Smil (2016, Chapter 1).

25 The English word ‘steel’ (like the German Stahl, the Dutch staal, the Nordic stål, the Russian сталь or стали, etc.) is derived from the nominalized Germanic adjective stakhlijan meaning ‘standing fast’, that is, being strong and hard, which in turn derives from Indo-European words for strength and firmness. The Mandarin Chinese sign for steel (钢 or gāng) has a similar origin, meaning ‘hard’, ‘strong’, ‘tough’. In contrast, the French word for steel, acier, derives from the Latin acies and, in turn, from Proto-Indo-European *h₂ek, meaning ‘sharp’ or ‘pointed’, and likewise the Hindi word for steel (इस्पात, ispāt) is derived from the Greek word for ‘blade’ or ‘sharp edge’ (σπάθη, spāthē). In any event, the various words for steel derive from the key properties of the artifacts made from it.

iron. Until then, the transformations by which steel was made were not understood, not only in hindsight but in the sense that the production of other alloys was.

Most practitioners and scientists tended to think that steel is really just iron its purest form. This notion was for instance reflected in Aristotle’s *Meteorology*. According to Aristotle’s discussion of the transitions of matter between solid, liquid, and gaseous form (what in modern physics is called the ‘phases’ of matter), materials like iron, ‘which solidify by refrigeration’,

‘cannot be dissolved except by excessive heat, but they can be softened — though manufactured iron does melt, to the point of becoming fluid and then solidifying again. This is how steel is made. The dross sinks to the bottom and is purged away: when this has been done often and the metal is pure we have steel. The process is not repeated often because the purification of the metal involves great waste and loss of weight. But the iron that has less dross is the better iron.’ (Aristotélēs, *Meteorology*, 383 a-b)

This was a reasonable empirical proposition, as steel obviously emerged as a result of a process of ‘purification’ in which iron was exposed to ‘excessive heat’. That view was predominant for more than two millennia. Thus, one of the first steelmakers to express his practices in writing, the master metallurgist Vannoccio Biringuccio of the city of Siena in Tuscany, maintained, following Aristotle, that steel ‘is nothing other than iron, well purified by means of art and given a more elemental mixture and quality by the great decoction of the fire than it had before’ (Biringuccio 1540, p. 67).

The theories of steelmakers, in spite of being based ignorant of the nature of steel, worked in practice, because carbon was the inexorable source of energy and thus ‘the inevitable accompaniment of any metallurgical process’ and, in fact, was present in ‘profusion’ in the smith’s hearth (Smith 1964, pp. 150 f.). The ‘secret of steel’, its being a carbon alloy, was well hidden because it was hidden in the open: in the glows of the steelmaker’s hearth.

It was only towards the end of the eighteenth century that it became definitely accepted among scholars, as one of the great insights obtained by the breakthroughs in chemistry, that steel is not at all ‘purified’ iron but rather an alloy of iron and carbon (Bergman 1781; Vandermonde et al. 1786). Nonetheless, the idea that steel is purified iron held sway in practice much longer, namely, until scientific metallurgy had something practically useful to add to the received recipes of the steelmakers. Until then, the new insight that steel is a carbon-iron alloy made no difference to practitioners, because they anyway used carbon in ‘profusion’ to make steel. For instance, as late as 1783, the French ironmaster and naturalist Georges-Louis Leclerc Buffon, wrote in his five-volume work on the natural history of minerals:

‘It seems to me […] that steel should be regarded as iron even more pure than the best iron: the one and the other are only the same metal in two dif-
different states, and steel is, so to say, an iron more metallic than simple iron; it is certainly denser, more magnetic, less dark in color, and of a much finer and more compact texture’ (Buffon 1783, vol. 2, p. 477; English transl. in Smith 1964, p. 151, n 8).

Because the nature of steel was an enigma, control of the transformation processes remained tentative and precarious. The enigmatic nature of steel reflected the fact that steelmaking was part of a specific ‘technical ensemble’, to use the term coined by Bertrand Gille:

‘Some complex techniques require […] a group of tributary techniques, the combination or ensemble of which is designed to perform a clearly defined technical act. Take the manufacture of cast iron, example […]: there are problems concerned with energy, with the components, the ores and fuels, the blast, and finally with the instrument itself — the frame, the refractory lining, and the shape. This is a good example of the ensemble whose every part is essential to the required result’ (Gille 1978, p. 14).

The techniques of traditional steelmaking were part of a ‘technical ensemble’ in which workers possessed no means of analyzing the composition of iron ores or bloomery iron for the purpose of controlling the input to making steel (other than color, texture, pedigree). Production was based on charcoal (or wood) as the source of energy, which limited working temperatures to a range well below the melting points of pure iron or of steel. Temperature was assessed by the color of the work piece and thus only within a temperature range of about 200 °C. The progress of the process could be assessed by visual inspection of the granularity in fracture surfaces of the steel. And so on. Altogether, traditional steelmaking was part of a ‘technical ensemble’ that afforded but very little control of the transformation process. Whether or not the transformation process succeeded relied entirely on the acuity and perceptual skills of the steel master.

In making steel, a range of extraordinary technical difficulties had to be faced and overcome. The major impediment to control over the production of steel, until well into the Industrial Revolution, was that steel products, in contrast to artifacts of precious metals such as silver and gold, or alloys such as brass and bronze, could not be produced by melting and casting, with the heat technologies available to metalworkers. The liquidus of pure iron is 1538 °C, and the iron-carbon alloys in the steel range can only be prepared for casting in the liquid phase at temperatures exceeding 1500 °C, that is, some 4–600 °C above the temperatures bronze age smiths and later metalworkers could confidently control. Instead, steelmakers developed different indirect strategies to make steel. Different types of strategy, each dominant for many centuries in different parts of Eurasia, can be distinguished.
Until the development of the blast furnace, and with that large-scale production of cast iron (in China from around 200 BCE, in Europe from around 1200 CE), the production of iron and eventually also steel in most of Eurasia began with the production of bloomery iron from iron ore (consisting of ferro oxides such as FeO₂, Fe₂O₃, Fe₃O₄, etc.). To smelt the ore, air was blown into a furnace containing iron ore and fuel (charcoal) so that a temperature of about 1200 °C could be reached. This is enough to ‘reduce’ the iron ore (i.e., break up the ferro-oxide molecules) but not to melt the iron. The result was a ‘bloom’, a spongy mass of low-carbon iron intermixed with slag. The bloom was, of course, of little use, but the resulting cake of low-carbon iron, intermixed with residuals of ‘slag’ (oxides of metal and silicon) was the raw material for the production of steel. First, the slag would be ‘liqutated away from the solid metal like water from a sponge’, by heating and hammering, a lengthy forging process ‘to consolidate the reduced iron and expel the residual slag’ (Tylecote 1987, pp. 114, 151). The reduced iron, ‘wrought iron’, would then have to be made into steel by means of a wide variety of very different techniques that in different ways relied on diffusion of carbon into the solid bloomery iron.

At this point we have to make a brief digression, for while diffusion of atoms and molecules in gases and liquids is a well-known notion, solid-state diffusion is certainly not; the phenomenon was only established well into the twentieth century. Since traditional steelmaking (unknowingly) depended entirely on exploiting this phenomenon, whereas contemporary steelmaking does not, a few remarks on this are necessary for understanding the historical specificity of contemporary steelmaking practices. Consider the ‘iron-carbon phase diagram’ again (Figure 14). The austenite phase rules the day between 727 °C and about 1400 °C (for a 0.76% C alloy). This phase was what provided the ‘degrees of freedom’, the space of possible moves, in which generations of blacksmiths, while unable to control the high temperatures required to obtain liquid steel for casting, nevertheless could develop and unfold their skills and make steel out of iron in the solid state. When a piece of iron is heated to above 800–900 °C, iron atoms will start vibrating wildly in the lattice, and if the environment of the hot piece of iron is rich with carbon (e.g., in the form of carbon monoxide or CO), carbon atoms are now able to move into and between cavities in the lattice, migrating from the carbon-rich environment, for instance, at the exposed surface, into regions of the iron were the carbon density is lower. That is, iron can be carburized and turned into steel in the solid state by a process of diffusion. The rate of diffusion is strongly dependent on temperature: At room temperature it takes years for a carbon atom to jump to the next cavity, but at 925 °C a carbon atom will jump back and forth between neighboring cavities 1.8 billion times per second. As a result of all this excitement, at 815 °C it will take a carbon atom 9.4 h to travel a distance of 1 mm, and at 1150 °C a carbon atom will be able to travel the same distance in 18 min (Verhoeven 2007, Chapter 7). That is, a piece of iron sufficient to make a knife immersed in a carbon-rich atmosphere at 1050 °C will be fully
carburized after a day or so. At 815 °C, however, complete carburization of the piece would take a month, which is undoable in practice.

Now, when the temperature drops below about 800 °C, the carbon atoms do not immediately ‘come out of solution’ but will migrate towards areas where the iron lattice is still in the face-centered γ form and where there is still room to accommodate them. Consequently, the concentration of carbon increases in these areas. When the steel cools further and the temperature drops below 727 °C, the remaining areas of face-centered γ iron transform into the body-centered α form. Carbon can now no longer be contained in solid solution and ‘comes out of solution’ in the form of iron carbide or ‘cementite’ (Fe₃C); a composite that forms hexagonal crystals, with carbon ‘interstitially lodged’ in the lattice structure, which is extremely hard and brittle (cf. Figure 16). The result of the slow precipitation of iron carbide is a lamellar microstructure, called ‘pearlite’, consisting of flakes of iron carbide alternating with flakes of ferrite. This has significant implications for the properties of steel, as pearlite provides for both hard and strong steel, but also steel that is deficient in ductility and toughness. A steel containing 0.76% carbon, is completely pearlitic (if slowly cooled). Below this limit, steel consists of pearlite regions intermixed with colonies of ferrite. Reduction of the grain size of the solid metal can also be achieved by mechanical treatment, typically in combination with controlled heating and cooling, for instance by hammering the piece (which is what blacksmiths have been doing in practice for centuries) or by rolling it.

In traditional steelmaking, without access to controlled temperatures in the 1540–1600 °C range, it was solid-state diffusion that made it possible for steelmakers to manufacture steel. This could take two directions: by carburization of wrought iron or by decarburization of cast iron.

Several methods were used to facilitate carburization by diffusion. Basically, the technique relied on immersing the solid bloomery iron in an atmosphere rich in carbon (CO) and low in oxide (CO₂) while maintaining a high temperature (well above 800 °C). Iron could, for instance, be carburized by heating pieces of bloomery iron for hours or days in a sealed crucible together with carbonaceous materials (e.g., charcoal). It was a technique that could deliver homogeneous steel, if the master could control the temperature of the kiln and the timing of the process, a big if. Alternatively, the smith could carburize the surface of the piece (‘case hardening’) by heating it in a hearth on burning charcoal, in an area away from the airstream from the bellows working to keep the fire hot. Or when cast iron was available en masse, as in China from 200 BCE, or became available, as in Europe from around 1200 CE, liquid cast iron from the blast furnace could be used as a source of carbon and thus as a means of carburization by submerging the piece of bloomery iron in a bath of liquid cast iron (of, say, 4% C), thereby creating a piece of steel, with a high-carbon and, consequently, hard but brittle edge and a low-carbon and softer but ductile core (for a contemporaneous recipe, cf. Biringuccio 1540,
K. Schmidt

pp. 69 f.). By means of yet another technique, used in China, a similar result could be obtained by layering sheets of low- and high-carbon iron that are then heated and hammered and, in effect, welded together (‘co-fusion’, Needham 1958; Wagner 1993; Needham and Wagner 2008). This would be considered steel in that some, perhaps significant, degree of diffusion would occur in the sandwich and that the lamellar piece anyway, on average, behaved like steel: being both hard and strong. Finally, it is worth mentioning the related technique developed by Japanese swordsmiths of ‘extraordinarily high levels of craft skill’ (Martin 2000, p. 90): Bloomery iron was broken into pieces and sorted according to the degree of hardness versus ductility of the pieces (based on their color and visible granularity in fractures). The pieces were then welded together, piece by piece, in a series of heating, piling, and folding operations. These operations, repeated about a dozen times, resulted in a piece of fairly hard steel with a uniform distribution of carbon, but to make a sword that was not only hard but also strong, the sheet of hard steel was folded around a core of softer, more ductile steel, and the whole thing was then hammer-welded into an oblong piece from which a lethal sword could be fashioned. These thermomechanical treatment techniques, developed over millennia, were the elementary and essential parts of the steelmaker’s repertoire. Until the second half of the nineteenth century, these were the primary means available to blacksmiths in Europe.

A historically important variant of carburization was used by early steel masters in Central Asia and on the Indian subcontinent who mastered the production of liquid steel, apparently from about 300 CE. The raw material, about 1 kg pieces of bloomery iron, was heated in a sealed crucible the size of a beer can to a high temperature (probably around 1000 °C) together with various carbonaceous materials (leaves and such), so that the enclosed slag in the bloomery iron would smelt and separate (and float to the top) and carbon from the carbonaceous materials would migrate, by diffusion, into the bits of solid bloomery iron, millimeter by millimeter, thereby increasing the carbon content and lowering the melting point (the same effect obtained by throwing salt on ice in the driveway). At the end, and after a lengthy cooling period, the crucible would be opened (crushed) and an ingot of reasonably uniform steel would appear and could be subjected to forging and the standard processes of hardening, tempering etc. (for instance for high quality swords). Recent archeological evidence suggests that crucible steel was exported widely in Eurasia and Africa and may have been the raw material from which the most exquisite Damascene knives and swords were fashioned (Verhoeven 2001). While such products were widely known and admired, the crucible steel process remained unknown to the wider world and the knowledge remained local, probably because it was a precarious process: it would take days to produce enough steel to be able to make a sword, and, more often than not, the result would of mediocre quality if not outright useless. And in any event, the quality of
The resulting steel did not surpass what could be achieved by manually controlled thermomechanical techniques. All in all, the cost of this steel was forbidding for most uses, that is, apart from luxury articles such as hand weapons for princes and their retainers.  

Last, in the alternative technique, *decarburization*, the direction of the process was reversed. Instead of carburizing wrought iron through solid-state diffusion, carbon was removed from liquid iron rich in carbon, such as cast iron from blast furnaces, by exposing the melt to oxidation so that carbon escaped as carbon monoxide. Over the centuries, various techniques for making steel by decarburization of iron evolved, especially in China, that became quite successful (Needham 1958; Wagner 1993; Needham and Wagner 2008).

Whatever the process, if the resulting iron was both hard and strong, it was the celebrated ‘steel’.

The enigmatic nature of steel — the fact that the ‘theory’ underpinning steel-making techniques and practices was nothing more that empirical generalization — comes across vividly in contemporaneous recipes and process specifications. An illustrative example of actual written recipes for steelmaking has come down to us in the form of a collection of recipes, possibly derived from an earlier oral tradition and only recorded in writing early in the Modern Era but in any event printed in 1532. The following recipe concerns the process of making steel by hardening iron:

‘Take the stems and leaves of vervain [*Eisenkraut*], crush them, and press the juice through a cloth. Pour the juice into a glass vessel and lay it aside. When you wish to harden a piece of iron, add an equal amount of a man’s urine and some of the juice obtained from the little worms known as cockchafer grubs. Do not let the iron become too hot but only moderately so; thrust it into the mixture as far as it is to be hardened. Let the heat dissipate by itself until the iron shows gold-colored flecks, then cool it completely in the aforesaid water. If it becomes very blue, it is still too soft.

You may also take human watery excrement after is has been distilled a second time and quench in that.

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26 The Hellenistic alchemist Zosimos of Panopolis from around CE 300 has left a detailed contemporaneous description of the crucible technique. The French translation by Berthelot (1888, p. 332) has been translated into English by Craddock (2003, pp. 243 f.). (On ‘crucible steel’, cf. Bronson 1986; Feuerbach 2002; Craddock 2003; Feuerbach et al. 2003; Srinivasan and Ranganathan 2004; Alipour 2017; Föll, No date [c. 2011]).
Or take red land snails, distill water therefrom, and then quench in this water.’ (Anonymous 1532, pp. 9–11).

To a modern reader, such recipes pose obvious problems of interpretation. On the one hand, the recipes today appear more fanciful than they probably were for a competent readership, in as much as deliberate obfuscation — a kind of encryption — for the purpose of protection of intellectual property may very well have been at work in composing the written recipe. For instance, one wonders if the author had actual evidence that the man’s or goat’s urine worked better than any urine on hand and if this extreme level of specificity was meant to confound competitors. On the other hand, there is anyway a metallurgical rationality in the recipes that is easily lost on modern readers. In the words of a historian of metallurgy, the use of ‘juice from earthworms’ and ‘other animal and vegetable concoctions’ may have been that using pure cool water from a creek for quenching may have made the steel cool too fast (Smith 1968, p. 5). What is important here, however, is that although the recipes are extraordinarily specific in the inventory of ingredients listed, they are otherwise quite vague. The language of the recipe is as loose as that of any handwritten cooking book passed down in a family, from grandmother to mother to daughter. Process specifications are practically absent or at best qualitative. For example, ‘Do not let the iron become too hot but only moderately so; thrust it into the mixture as far as it is to be hardened’. That is, the recipe leaves it to the practitioner to determine the point in time where the iron has reached the desired temperature as well as the depth to which it is to be submerged in the quenching bath. In sum, the recipe is not an ordered set of steps, a script to be enacted, but rather a set of codes for rules of thumb that were only useful to practitioners who had already been trained in making such assessments and for whom they probably merely served as an aide-memoire.

That the control of the process was left entirely to the ironmaster’s discretion seems to have been the norm in Medieval and Early Modern recipes. It is, at any rate, evident in what is deemed to be the ‘first good description of steel making’ (Smith 1964, p. 152), namely, Biringuccio’s description of the technique for making steel by submerging a piece of wrought iron and heating it in a bath of melted cast iron and then subsequently quenching it in cold water:

‘Having previously made under the forge hammer three or four blooms weighing thirty to forty pounds. each of the same iron, they [steel masters observed by Biringuccio] put these while hot into this bath of molten iron. This bath is called “the art of iron” [larte de ferro]27 by the masters of this

27 The editor of the critical edition of Biringuccio’s book points out that this is probably a typographical error in the Italian original: instead of larte di ferro, read latte di ferro, ‘the milk of iron’.
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art. They keep it in this melted material with a hot fire for four or six hours, often stirring it up with a stick as cooks stir food. Thus they keep it and turn it again and again so that all that solid iron may take into its pores those subtle substances that are found in the melted iron, by whose virtue the coarse substances that are in the bloom are consumed and expanded, and all of them become soft and pasty. When the masters observe this they judge that that subtle virtue has penetrated fully within; and they make sure of it by testing, taking out one of the masses and bringing it under a forge hammer to beat it out, and then, throwing it into the water while it is as hot as possible, they temper it; and when it has been tempered they break it and look to see whether every little part has changed its nature and is entirely free inside from every layer of iron. When they find that it has arrived at the desired point of perfection they take out the lumps with a large pair of tongs or by the ends left on them and they cut each one in six or eight small pieces. Then they return them to the same bath to heat again and they add some more crushed marble and iron for melting in order to refresh and enlarge the bath and also to replace what the fire has consumed. Furthermore, by dipping that which is to become steel in this bath, it is better refined. Thus at last, when these pieces are very hot, they are taken out piece by piece with a pair of tongs, carried to be drawn out under the forge hammer, and made into bars as you see. After this, while they are still very hot and almost of a white color because of the heat, in order that the heat may be quickly quenched they are suddenly thrown into a current of water that is as cold as possible, of which a reservoir has been made.’ (Biringuccio 1540, pp. 69 f.).

The point of reproducing this description at length is this: ‘When the masters observe this they judge that …’ and ‘When they find that it has arrived at the desired point of perfection …’. That is, presuming that Biringuccio’s account is a faithful rendition of what the steel master told him, the traditional recipes were loosely expressed qualitative associations: ‘First do this, and then that, and the result should look or feel something like this; if not, start over’. Everything depended on the manual and perceptual skills of the individual steelmaker, his ability to determine the temperature of the charcoal and the work piece in the hearth or on the anvil, the airflow from the bellows, the granularity of steel in

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28 That the description given by Biringuccio was deemed a useful and workable recipe by contemporaries in general and by metalworkers in particular is underscored by the fact that Agricola in his famous De Re Metallica (1556) simply paraphrases Biringuccio’s description (Smith 1968, pp. 22 and 25, note c), and that Agricola’s De Re Metallica for centuries was used as a reference work by miners and metalworkers. It was obviously considered standard operating procedure. ‘It is our impression that the whole of this discussion on iron in De Re Metallica is an abstract from Biringuccio, who wrote 15 years earlier, as it is in so nearly identical terms’ (editors’ note in Agricola, 1556, p. 420, n. 55).
a fractured piece, etc. (for a similar assessment, see Long 2001, p. 74). In any event, the ‘technical ensemble’ to which the practices described by Biringuccio belonged could not offer anything more specific than this in terms of process control. All in all, steel was made by virtue of highly sophisticated craft skills of steelmakers (see also Sherby and Wadsworth 2001, p. 347).

Because of these severe limitations, in addition to highly refined manual and perceptual skills, making steel also required excessive time and toil. For in spite of all the effort and the highly developed skills, the process was precarious: ‘steel was made on a hit-and-miss basis from the start of the iron age, and the quality of such steel varied widely’ (Verhoeven 2007, p. 10). Even the Japanese swordsmith, with his ‘extraordinarily high levels of craft skill’, ‘would expect to lose over half his work’ (Martin 2000, pp. 90, 98). The Japanese artisans had little control over the process. The exquisite swords on display in museums are the tip of a gigantic iceberg of wasted labor, wasted iron, and forests laid waste. By and large, these recipes worked because the product, if expectations were met, was of such value that days or weeks of toil and a high rate of misses were a tolerable cost. But this also meant that products made of steel were expensive and way beyond the means of ordinary people (Feuerbach 2006; Williams 2007).

Steel remained a rare commodity until the end of the eighteenth century, when the ‘puddling process’ was introduced (Tylecote 1992, Chapter 9). In this process, wrought iron was produced by decarburization of cast iron. This was achieved by continuous stirring (or more correctly turning and pushing) of molten pig iron with long rods (rakes) through the doors of reverberatory furnaces (fired with coke) in order to decarburize it (by exposing it to oxygen) and producing a nearly pure metal containing less than 0.1% of carbon’. This iron could then be transformed into steel by the ‘cementation’ process, in which iron billets were exposed to prolonged heating in charcoal in a sealed vessel. The result was a steel of mediocre quality. But around the middle of the eighteenth century a technique was developed to make quality steel for special purposes from puddling iron. The important precondition was the use of coke as fuel to reach a sufficiently high temperature (1600 °C). Steel could now be melted down in crucibles and then cast into a mold as an ingot. Although this process involved multiple stages and required several days of work to produce one small batch (20 kg per crucible charge), it held the stage until the second half of the nineteenth century. Anyway, this technique could not sustain large-scale production of quality steel, and the ‘the resulting output was still used for relatively small items of artisanal provenience: as before, for expensive hand weapons, and increasingly for razors, cutlery, watch springs, and metal-cutting tools whose quality and dependability justified higher prices’. (Smil 2016, pp. 32–34).

Until well into the nineteenth century, steelmaking techniques remained what they had always been: little more than a set of rules of thumb, recipes, and procedures that had evolved over centuries, through trial and error, and passed down,
typically orally, from master to apprentice in a long chain of generations, with setbacks and false starts, with knowledge lost to the untimely death of key links in the generational chain due to war, plague and similar misfortunes, but still with some accumulation of knowledge over the centuries and millennia (cf., e.g., Long 2001). Steelmaking remained entirely predicated on the perceptual skills of the workers: on their acquired ability to distinguish color, odors, levels of heat, textures, and grain patterns.

The Bessemer process, invented in the 1850s, heralded a departure from all that. Given its high content of carbon, cast iron provides an excellent source of energy that can be released by blowing oxygen (in the form of compressed air) into cast iron in the liquid phase. This triggers a violent combustion in which carbon is oxidized and is released in the form of carbon monoxide and other gases, the temperature shoots up, and the resulting steel can be used directly for casting. It was only with the further development of this technique that the severe limitations of the various received craft techniques for steelmaking based on forging were overcome and mass production of steel developed as an industry. However, it was soon realized that the original Bessemer process suffered from the major disadvantage that it could only produce usable steel if the cast iron used was virtually free of phosphorous. By contrast, the Siemens-Martin ‘open-hearth’ technology, developed over the following decades, could handle all kinds of ferrous input, including scrap, and it won the day and remained dominant until late in the twentieth century. Contemporary steel production is based on variants of the family of technology inaugurated by the Bessemer process, mostly in the form of Basic Oxygen Furnaces (BOF) developed after the Second World War, and also, partly but increasingly, in the form of Electric Arc Furnaces (EAF), where oxygen blowing is applied to increase the temperature and burn off impurities in the melt. The technologies that have made it possible to achieve and maintain the very high temperatures at which iron and alloys of iron are in the liquid phase or state have reduced the complexity of the process immensely and have provided the practical technical platform for rigorously controlled production of steel.

These advances notwithstanding, steelmaking long remained entirely predicated on the perceptual skills of the workers. To take an example, for illustration, a British steelworker, Patrick McGeown, has given a description of the precarious nature of steelmaking in open-hearth furnaces (of the kind that existed at the Steel Plant until the late 1970s). Describing the work of his father’s generation of steel workers in the early years of the twentieth century, he says:

‘every pot of steel was an act of creation. It was something derived from the absorbed attention of dedicated men. So dedicated, so absorbed, that often they overlooked the misery and the hardship of their lives. They had been given a chance to create, and that made up for plenty.’ (McGeown 1969, pp. 56 f.).
He goes on to report on his own work as a steelworker some twenty years later, around the middle of the twentieth century:

‘Though greatly improved on, the furnaces were still vulnerable, and steelmaking was still a chancy thing where the metal didn’t always flow the right way up. There were still wet shirts and plenty of anxious moments for melters, and always the great satisfaction of seeing one’s charge surging from the furnace to the ladle. Then the melters felt like sea captains who had brought their ships safely to port after a long stormy voyage.’ (McGeown 1969, p. 61).

The critical issue was, still, temperature control. Workers relied entirely on perceptual skills in determining the temperature of the melt:

‘On basic open-hearth furnaces the melter’s craft is not in his hands but in his eyes. Through years of gazing in the white heat of furnaces he acquires a sort of secondary sight, as if his eyes have special compartments for the judging of furnace temperatures. Previous to the increased instrumentation on melting shops, the melter’s eyes were almost his only guide to controlling heat. […] It was that inconsistency in heat control, for we were only human, that helped to make our steelmaking a hit or miss affair. Where sometimes we could produce a ladle full of beautiful steel within four hours from filling the furnace, there were other occasions when the same type of steel took seven or eight hours to produce.’ (McGeown 1969, pp. 61 f.).

However, around 1950, major advances in temperature control was achieved:

‘It gave us our first control panels on the furnaces, they saved us much manual labour and were a big step towards precision steelmaking. It was pleasant to regulate the oil, steam and air flows by the touch of a button compared to the hauling we used to have on the old-time gas and air valves.’ (McGeown 1969, p. 66).

The revolutionary transformation of the steel industry that McGeown, at the end of this essay, anticipated would happen before the end of the century, a transition to ‘instant steelmaking’, were, in large part, due to advances in scientific metallurgy.29 For our purposes it will suffice to note the major advances.

The theory of steel as represented in the phase diagram for the steel-carbon system was developed over several decades at the end of the nineteenth century.

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First, it represents series of intense empirical research. On the one hand, it reflected the enormous effort of chemical analysis of steel of different properties to determine their chemical composition. This work had been ongoing since Bergman carries out 270 experiments with steel of widely different hardness (1781). (For overviews, cf. Smith 1964; Tylecote 1992, pp. 178 f.). This effort now unfolded to include varying temperatures based on the invention of temperature sensors that could survive in the environment where steel is made. This was finally made possible with the development and use of pyrometers that exploit the regular variation of electrical resistance in metals with varying temperatures, in particular rhodium-platinum thermocouples (e.g., Le Chatelier 1887). This triggered intense empirical research to map the properties of steel of different composition, from 0.08% to 1.25% C, at different temperatures, from room temperature to beyond the melting point (e.g., Osmond 1890; Tammann 1903). The results of the empirical mapping effort were given a thermodynamic interpretation and thereby a theoretical foundation (by, e.g., Roberts-Austen 1899; Roozeboom 1900; Roberts-Austen and Rose 1901a, b), based on the earlier work of Willard Gibbs (1875–1876, 1877–1878). Thus, by 1901 ‘we see a nearly correct iron-carbon equilibrium diagram based on the phase rule of the accepted thermodynamic principles of chemistry’ (Tylecote 1992, p. 181). The phase diagram of the iron-carbon system had been established (Figure 14). The outcome of all this was a calculus that made metallurgists able to ‘predict the phases present in alloys at different temperatures’ (Mossman 2003, p. 515).

Parallel to these efforts, metallurgists investigated the internal structure of steel. As already noted, steelmakers had long since observed that a steel piece, when broken, exhibited a granular structure at the fracture surface. Toward the end of the nineteenth century, the structure of steel was subjected to systematic studies by means of optical microscopes (Sorby 1886; Roberts-Austen 1891). What appeared in the polished and etched surfaces of steel under very large magnification indicated that the grains are indeed crystalline. Beyond that, no progress was possible until the discoveries — around the turn of the twentieth century — of the electron (J. J. Thomson in 1897) and the development of the theory of the structure of the atom (by Ernest Rutherford and others, in 1908–13) and of quantum mechanics (by Max Planck in 1900, Albert Einstein in 1905, Niels Bohr in 1913, etc.) opened the internal structure of metal and other solids for close inspection. For the metallurgy of steel, the crucial step was the discovery of X-ray diffraction in 1912. This ‘enlarged the bounds of metallurgical science’ (Tylecote 1992, p. 181). By virtue of this technique, the lattice structure of metals and alloys was mapped out in the course of the following decade (Ewald 1962). And when X-ray diffraction was finally applied to the study of alloy constitution by Alan Westgren and Gösta Phragmén (1922), ‘the structures of alpha, beta, gamma and delta iron finally resolved’ (Tylecote 1992, p. 181). This was followed in the 1930s with the development of the theory of ‘dislocation’ within
crystal lattices as a source of metal strength (e.g., the account of hesitant steps in Hume-Rothery 1936, Part VI). This hypothesis was verified in the 1950s when the transmission electron microscope became available and allowed scientists to actually see dislocations as they happen. In addition, toward the end of the twentieth century, analytic technologies like the electron microscope, field-ion microscope, and high-resolution electron and atomic-focus microscopes have revealed the internal structures and processes at the level of the crystal lattice of steel, at the atomic level. Crucial phenomena such as the solid diffusion of carbon and other elements as well as the interstitial presence of carbon within the lattice, which by the turn of the century had been hidden in obscurity, had now been documented.

In sum, then, for centuries, steelmakers produced steel without an inkling of the nature of steel, its being a carbon alloy of iron; without technical means of measuring composition and temperature; and hence with only precarious control of the process. Practical knowledge was strictly empiricist, and production relied entirely on the perceptual and manual skills of workers. Only in the course of the last 100–150 years was the nature of steel investigated systematically and understood sufficiently to allow for steel to be produced on a large scale, as a commodity. More than that, contemporary steelmaking was made possible only by the advances the metallurgy of steel has made over the last century and especially the last 60 years. Where steelmaking traditionally was based on (unknown) processes of solid diffusion of carbon engendered by thermomechanical treatment, it is now based on (carefully controlled) processes of melting, chemical treatment, and casting. The technical basis is entirely different. Steelmaking practices, consequently, are now applications of technologies that are radically different from the traditional techniques of steelmaking. Contemporary steelmaking practices are applications of scientific knowledge. The first impression of the visitor to the Steel Plant — of something ‘like Dante’s hell’ — is just that: a first impression. The practices of traditional and contemporary steelmaking are incommensurate.

5.2 Steelmaking 101

The steelworkers are far from novices: they know their art, and — this is crucial — their art is grounded in metallurgic education.

In fact, long before the ethnographer arrived at DDS and began trying to make sense of it all, sophisticated metallurgical knowledge had been acquired and become an essential foundation of the Steel Plant work organization.

It is significant that the education program was developed in response to an expressed demand from steelworkers. This demand arose as the challenges posed by the new technologies of electric arc melting, continuous casting, and secondary steelmaking in ladle furnaces became clear in the 1980s. Thus, hand in hand with the Steel Plant’s conversion to the new technologies, an education program was developed. Already in the late 1970s and early 1980s, courses on steel
metallurgy were held for shopfloor workers. But the rapid development of the technologies of steel production from the 1970s intensified the need for increasing the level of metallurgical education on the shopfloor.

As noted, already from 1975, tentative steps toward continuous casting were taken, and in 1985, the Ladle Furnace was acquired and installed. Production with the new setup was launched in 1986. This changed the work organization radically. Until then, steel had been cast as ingots which then had to be hot-rolled to be turned into steel bars or plates. With this traditional technical setup, work was overwhelmingly handicraft work; that is, it largely relied on the workers’ immediate perception of the state of the steel, the color and viscosity of the slag, and the equipment. After steel had been produced in the open hearth-furnaces and before casting, only little further treatment, was possible, beyond the addition of fluxes (Burchardt 2009). In terms of coordination among workers, ingot casting was a highly localized affair, performed by a relatively small team working in proximity within the same shop and able to see and (some of the time) hear each other and thus to coordinate their activities fairly easily, by implicit mutual adjustment interrupted by occasional shouts and gestures. Work was of course time-critical, in as much as steel in ladles loses energy and reacts with the refractory materials of the walls of the ladles and with the atmosphere, but the workflow consisted in short and discrete cycles, defined by the handling of one charge at a time, and thus with little or no risk of delays propagating downstream, and even if a critical delay did occur, for some reason, and casting had to be interrupted, the economic loss of reheating the melt in the furnace was not forbidding; it was a manageable risk.

With continuous casting, this changed, for the scope of the operation now expanded considerably to span a wider space with multiple stations. Workers no longer had direct access to perceive the state of the process beyond their local station. For that they now had to rely on verbal communication with colleagues at other stations. Furthermore, also because of the required strict continuity of casting for several hours, the operation became acutely time-critical as interruptions of continuous casting now became exceeding costly.

Consequently, coordinative practices evolved in which the Casting operators took on or were given the role of conductors marking the rhythm of the preceding processes of melting and refining. To meet that task, they had to take into account the state of affairs at remote stations, which in turn required reasoned anticipation of the progress of melting and refining as well as verbal exchanges with operators at those stations. In response to this change in the qualifications required, the Steel Plant began to organize courses in general steel metallurgy.

The introduction of the ladle furnace in 1986 implied yet another major change, as not only refining but also temperature adjustment and the entire range of alloying tasks now (in principle) would be performed at a separate station between EAFs and Casting. The responsibility for meeting the quality
and temperature requirements of the product and for doing so in time was now shifted to the Ladle Furnace and, consequently, so was the function of beating the rhythm of the whole operation.

Now, secondary steelmaking using ladle furnaces was a quite new technology and very little experience was available, so when the decision to acquire the ladle furnace had been taken, things became very agitated. It was obvious that the new technology would pose serious challenges in terms of organization, planning, and procedure. Department meetings and meetings of the local Safety Committee, comprising plant management and shop stewards, often turned into lengthy and excited technical discussions. According to a shop steward deeply involved in the discussions at the time:

‘We had this engineering manager out there, a Steel Plant boss, who from time to time joked that he knew that he, when the discussions [about safety] during meetings in the Safety Committee became too [politically] heated, simply had to guide discussions towards production, for we then would forget everything about the discussions about safety.

But out of all these discussions arose a need to have some courses [addressing ladle furnace technology in particular and metallurgy in general]’. (Interview with Jørgen Andersen, 2006, 00:11:28).

To prepare the organization for the new ladle furnace, a delegation was sent to Seiko Steel in Japan, the vendor of one of the only two computer-based control systems for ladle furnaces available at the time on the market. The objective of the trip — a field trip, actually — was for the workers to be introduced to the system, to practice using it, to learn from steelmaking practices at the Japanese plant in general, and based on that develop an education package, a curriculum with reading materials, for the workers back in Denmark to add to the materials already being taught. After the field trip, the observations formed the basis for an Introduction to the Ladle Furnace, authored by the shop steward and one of the other workers for their colleagues. This Introduction was basically a guide

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30 In addition to the shop steward and other steel workers, the delegation included foremen and an engineer.

31 The text of the Introduction seems to have been lost. Only fragments of it have been located in the binder kept at the console in the Ladle Furnace. However a primer for Steel Plant workers from around 1990, written by one of the engineers at the Steel Plant, which presumably covers the same topics, consists of seven chapters: ‘Steel and steel products’; ‘Scrap and Other Raw Materials’; ‘Melting’; ‘Refinement’; ‘Ladle Furnace Treatment’; ‘Casting and Adjustment’; and ‘Hot-rolling and testing’ (altogether c. 115 pages). Supplementary instructional memos are also kept in the binder; for instance an undated memo in 7 pages (signed by HEN and, to judge by the typography, from around 1986) entitled ‘Stålets følgestoffer’ (‘The foreign elements in steel’), which covers the chemical properties and effects of the whole range non-ferrous elements in steel from alloying elements such as carbon and manganese to pollutants like phosphorous. The copy of the extant memo carries handwritten annotations, presumably by a worker reading it, summarizing the critical effects on steel of the more important elements. Yet another memo, also by HEN, explains the periodic system.
to practical metallurgy, providing practical recommendation as well as metallurgical explanations.

The curriculum covered the following central topics in the general metallurgy of steel:

- Properties of steel: hardness, tensile strength, hardenability, weldability.
- The lattice structures of iron and steel; the grain structures of steel.
- The phase diagram of steel.
- Alloying elements and impurities and their effect on the properties of steel.
- The carbon equivalent (Ceq).
- The different steel qualities.

Complementing the general metallurgy of steel, the steelmaking equipment and processes were covered in some detail:

- **Scrap:** the production and composition of raw iron; the composition of scrap from different sources; methods for sorting scrap and for packing the basket with scrap.
- **Melting:** main structural and functional characteristics of the electric arc furnaces; chemical reactions in the melt and between the melt the atmosphere; the use of oxygen-blowing to decarburize and remove phosphorous; the function of fluxes in initial refinement; the composition of slag; key sample measurements and analysis results.
- **Ladle furnace treatment:** main structural and functional characteristics of the ladle furnace and associated facilities (for delivering alloying elements and fluxes); the structure of ladles; methods of desulfurization; function and method of argon-blowing; key sample measurements and analysis results.
- **Casting and adjustment:** the structure of the billet and slab casting machines; the structure of the tundish; methods of temperature control during casting; methods of preventing re-oxidation of aluminum-killed steel and clogging of molds; methods of preventing reaction with atmospheric nitrogen; methods of preventing micro-slag enclosures and colonies of foreign compounds such as MnS in the core of the solidifying steel that may ‘trap’ hydrogen within it.
- **Hot-rolling and testing:** the structure and phases of steel; the crystalline structure of steel; grain growth; normalization and recrystallization; methods of testing steel for tensile strength and ductility.

The steel workers obviously were prepared to develop practical mastery of ladle furnace technology and the new overall process based on it.

5.3 Congealed labor: precomputation

It goes without saying, but has to be said anyway, that the ongoing work at the Steel Plant plays out within an organized setting. Nothing could and would happen if it
was not for a range of preparatory activities that provide an organizational framework for the task trajectory that begins when scrap is collected and dumped into an EAF, the power-on button is pressed, and the electric arc lights up. The cooperative work arrangement, first of all, needs to be mobilized and deployed. This is done by means of a set of lists that, on the one hand, assigns individual workers to the various work stations, divided into five shifts (‘teams’), and specifies their responsibilities, and on the other, assigns managerial responsibility for the different stations and describes the chain of command. Updated occasionally, when there has been a change of staff, or staff are absent due to vacation, sick leave, etc., these lists serve to specify a relatively stable organizational framework that then can be taken for granted.

When the cooperative work arrangement has deployed and workers have clocked in, the ongoing work is coordinated by means of a set of interconnected coordinative artifacts, an ‘ordering system’ (Schmidt and Wagner 2004), consisting of, in particular:

- The Product Type Catalogue.
- The Production Plan.

The product type catalogue  Iron’s affinity for forming alloys of the most diverse kinds, its extreme metallurgical promiscuity, creates a potentially intractably large problem space. For artisanal steelmakers this was a major issue, one that they were unable to master, as they had no effective control of the chemistry of the input. However, the practically infinite space of possible permutations has been made manageable by the contemporary steel industry’s standardized product specifications that defines Product Types according to composition and structural properties. Furthermore, at the Steel Plant itself, the number of possible permutations is further reduced to a catalogue of about 200 Product Types. This has made the challenge posed by the affinity of iron for forming alloys somewhat tractable. The operational complexity arising from a practically endless space of possible product types, with different procedural requirements and output specifications, has thereby been reduced significantly.

The Product Type Catalogue specifies, for each Product Type, the composition and temperature that, according to metallurgical calculation, are required to achieve the intended properties of the specific steel type. It is a precomputed recipe (Figure 17).

The Product Type Catalogue is available to operators as a set of protocols in the Ladle Furnace’s computerized control system (Figure 18). Here, the target values for each of the alloying elements are displayed synoptically, next to the values predicted for the same elements on the basis of the measured values.

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According to the latest laboratory report, the system furthermore supports interactive calculation of the effect of the different alloying elements. In the words of the functional specification of the control system:

‘The system incorporates a model that calculates the admixture of alloying materials based on: desired analysis, initial analysis [at tapping], charge weight, the chemical composition of the [added] alloying materials, the effect [Ceq] of alloying materials’. (‘DDS-skeovn: Funktionsspecifikation, rev. 1.3’ (‘DDS Ladle Furnace: Functional specification’, v. 1.3), 20 August 1985).

Based on this ‘model’ (or computational protocol, i.e., a digital representation that can used for calculations), the system’s ‘recipe screen’, for instance, shows the projected final analysis (minimum, ideal, and maximum values) together with a list of the relevant alloying elements and their effect (Ceq).

In other words, as a precondition for ongoing coordinated steelmaking, engineers have been at work, at their desks, constructing and maintaining the Steel Plant’s Product Type Catalogue with its 200 or so protocols, each of which is based on standard metallurgical knowledge and calculations as well as accumulated local experience with the specific issues to be taken into account in action with respect to each Product Type.

The ladle furnace process protocol The Product Type protocol is complemented by the process specification that expresses the prescribed sequential order and timing of the steps involved in refining and alloying a charge of given type of steel at the Ladle Furnace (Figure 19).

It so happens that we know how the set-up of the operations was calculated when the novel ladle furnace was introduced in 1985–86. It was initially done during the previously mentioned field trip to Japan in 1985 and was of immediate operational significance. As later described by the shop steward, the story is this.

‘I saw casting [at Seiko Steel, Japan] that was largely continuous. […] But they could keep it together, so that they practically could go on casting forever. They had pretty long transportation routes, from where ladles were ultimately completed and then taken to the tower: they knew how to do that, too. […] It was really wildly impressive, for it worked, it worked!’ (Interview with Jørgen Andersen, 2006, ca. 00.02:45).

‘We observed the way in which they … worked together in groups. First of all, they weren’t particularly busy. They didn’t bloody toil. They went about
their work, and they knew incredibly much about what they were dealing with.’ (Idem., ca. 12:40).

‘When we [eventually] had participated in the production and we had observed these things, there was one thing [in particular] we had realized, namely, that they had very long time for making such a charge ready. They had three quarters of an hour from the time they received it until they had to have it ready in terms of temperature, analysis, and to have it refined; that time we did not have at all. […]’ (Idem, ca. 15:00).

So the delegation turned to the chemical engineers assigned to them, indicating that they needed a chat.

‘One hour later, the chief metallurgist of Seiko Steel, possibly one of the ten leading metallurgists in the world who know most about the production of steel, arrived, and we talked to him about how we might manage. We did not at all have the time they had. We only had half: 20, at the most 22 minutes.’

To the surprise of the delegation, the metallurgist replied that he would have to call the ‘experts’, and again to their surprise, it turned out that the experts were the very same Japanese steelworkers they have been around every day. They explained their predicament:

‘They then ask us a lot of questions: “Which temperature do to need for casting?”．“What’s your Liquidus?”．“What kind of analyses do you have?”．“What is your target?”．“What do you receive from the furnaces?”．“What kind of refractory are there in the ladles? Is it chamotte or what? And what lime does it release?”．They asked a series of questions, really many. We answered them. We were clever too, not as clever as them; but we knew [the answers]. And they took notes and notes. At some point they had all they needed and went aside and talked and talked. They sat there with their slide rules (they didn’t even have pocket calculators) and talked.’

After some time, the Japanese workers went to the blackboard and, with the help of the interpreter, explained (pointing to a workflow diagram):

“Here you receive it. You have to have at this particular temperature, or you’ll be in trouble, for you need some temperature to lose. And since you have so little time, you have to add lime immediately. You then
have to heat it as long as you can, but you should not heat it for longer than four minutes each time. For with the chamotte you’ve got there, it’ll start eating. You’ll have a slag zone. It’ll be an acidic slag there if you do it. Four minutes at the most, initially, first time you power up, and so and so and so. And you [need to have] the analyses right there, for you also know how much time will pass from you take the sample until you have the analysis.”

In complete detail, how we should do it.

The recipe these guys made for us, we took that home and included in our course program for how to run it [the Ladle Furnace]. It is, by and large, the procedure that has been used from Day One until it [DDS] closed. Things have of course been modified along the way, but other than that, it is what is being done. [Citing the message from the Japanese workers]: “So, sure, you can make it work, and on top of it, you have two minutes if something goes wrong.” I was really impressed with them. They knew it! They knew it! They knew it!’. (Ca. 00:20:50 ff.).

The calculation produced by the Japanese steel workers was subsequently validated, or possibly just authorized, by the engineers at the Steel Plant. This is done in a fairly tentative and informal process specification dated 7 January 1986 that expresses the prescribed sequential order and timing of the steps involved in refining and alloying a charge of a given type of steel at the Ladle Furnace (see Figure 19). The process is specified in greater detail in the associated text.33

It is important to note that as late as January 1986, that is, after the acquisition of the ladle furnace and after the delegation’s visit to Japan, the engineers at the Steel Plant indicated significant reservation as to whether the new configuration left sufficient time to afford the scale of continuous casting they were aiming for. In the words of the January 1986 memo:

‘Whether the ladle furnace is an unmitigated advantage over the TN facility [which previously served to prepare charges for casting in a manner similar to the treatment at the ladle car], is difficult to say, as we have become pretty

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33 The process specification exists in two versions, a fairly tentative and informal one with the title (Skeovn’ (‘Ladle furnace’) from 7 January 1986, and a much more elaborate and rigorous one with the title ‘Process specification’ issued a decade later, on 14 October 1996. Both versions are held in the red binder kept at the Ladle Furnace console (Figure 18).
good at desulfurization. Furthermore, the ladle furnace has a minimum processing time of about 25 minutes, but because we have become far better at controlling the temperature, it is hardly a significant drawback.’ (‘Skeovn’ (‘Ladle Furnace’), internal memo dated 7 January 1986, authored by HEN.)

That is, it was obvious to all involved, from the very beginning, that the whole set-up would be working under severe temporal constraints. The continuous casting operation based on two EAFs and a Ladle Furnace in between was in dire straits from the outset. Strict timing was essential. The plan for that was established with the timing scheme first calculated during the meeting at Seiko Steel and afterwards presumably validated by the engineers at the Steel Plant and which underlies the daily Production Plan for the plant.

**The production plan** For each 24-hours period, beginning at 06:00, a general Production Plan is worked out by the plant’s managing engineers and distributed to all stations in the Steel Plant (Figure 20). It specifies the amount of steel (in tons) of different Product Types that is to be produced for each day.

The planned schedule is expressed in Product Type Codes (e.g., ‘S-23’) and thereby includes a reference to the Product Type Catalogue. By specifying the Product Type Code, the plan (indirectly) specifies the composition of the alloy, the Ceq, the temperature at which steel is to be handed over to Casting, and other vital statistics. The schedule also indirectly depends on the Ladle Furnace Process Protocol, as this expresses the minimum turnover time at the Ladle Furnace and thus gives the calculated time unit of the schedule. In calculating the Production Plan, the managing engineers of course also rely on their knowledge of average lapse time per charge at the EAFs and in Casting for the different types of product, as well as the number of charges that can be reliably achieved per casting sequence.

The daily overall Production Plan gives the workers at the different stations a rough idea of what is to be done, in which order, and the tempo they can expect. The Ladle Furnace operator has the plan in front of her on her console (Figure 20). In the course of the day it is used as the frame of reference when new casting sequences are starting, or when there for some reason is delay or some other glitch in the flow of production. Given the shift plan and the Production Plan, when workers clock in, they roughly know what is to be done, in which order, and by whom. The trajectory is known before ignition, so to speak; that is, the configuration of the work organization of the day is taken for granted as all workers go about their work.

However, issued only once every 24 hours, the plan does not reflect the unfolding state of affairs. It thus does not provide the continually updated global representation of the state of affairs (according to certain key coordinative criteria) that coordinative artifacts provide in other settings (such as, e.g., the flight database connecting air traffic control sectors, the fixed line displays of urban rapid transit control centers,
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It has more in common with the weekly or daily master schedule of manufacturing planning and control or the project schedule and fault reports of design projects (Schmidt 1991b; Pycock and Sharrock 1994; Bowers et al. 1995; Carstensen and Sørensen 1996; Carstensen et al. 1999; Carstensen and Schmidt 2002).

That is, behind the dramatic scene of melted steel and moving ladles lies an extensive and manifold division of labor, encompassing, on the one hand, the engineering work of producing and maintaining the Product Type Catalogue and lists of average production time for different products and casting sequences, and, on the other hand, the administrative and managerial practices of corporate HR and local foremen.

This provides a key piece of the answer to our question: How do the distributed workers manage to produce quality steel at a high rate? No mysterious shared mental state (‘mutual awareness’) need to be invoked, nor do we need to adduce some, equally mysterious, underlying ‘formal structure’ or ‘sequential organization’. Rather, the answer to our question is, in part, that the temporal order of the overall operation and its component steps has been meticulously planned and calculated; it is very much ‘precomputed’, to use a term suggested by Don Norman and Ed Hutchins (1988; cf. also Schmidt 1997).

6 Coordinative practices of the second order: discursively organized activities

Let us now see some action. Transforming the Production Plan and the recipes of the Product Type Catalogue, and the Ladle Furnace Process Protocol into ‘situated action’, into practice, involves occasional discursive planning and other verbal exchanges. So, first, let see some speech action.

6.1 Count-down procedures

Converting the Production Plan into an operational schedule involves some phone or intercom exchanges or even conversations with operators at the other stations, especially at Casting. It ordinarily goes something like this.

An afternoon in June, at 14:15, the Ladle Furnace operator (LF) calls Billet Casting (BC) on intercom:

Fragment 1 (14:15)
LF: ‘Ladle Furnace.’
BC: ‘Yes?’
LF: ‘What’s the plan?’
BC: ‘What?’
LF: ‘You know, about when to start up, how much shall we make and the like. I thought you had talked to [the foreman].’
BC: (In a voice pretending to sound taken aback) ‘We bloody well haven’t talked to him.’

LF: (Soothing voice, in jest) ‘Well, well…’ [Serious now:] ‘When do you have the tundish up and running?’

BC: (Calculating aloud) ‘It’s now 14:15, it then becomes 16:15, that is, it will be 16:45.’

LF: ‘Very well then, you’ll receive x charges [starting] at 16:45.’

LF: (Switches off intercom and says, addressing no one in particular) ‘16:45… Bum, bum.’

To take a rather less ordinary example, consider this chain of events unfolding over another afternoon in June. The operators at the different stations are busily engaged in a slab casting sequence. At the same time, the Billet Casting operators are preparing a sequence of billets (‘K374’). At 15:03 EAF B has tapped charge #67B, its last contribution to the slabs casting sequence, and the operators are now preparing to produce the first charge for the billet sequence, but then at 15:15 the operator of EAF B calls Ladle Furnace over the intercom:

**Fragment 2.1 (15:15)**

EAF B: ‘Ladle Furnace?’

LF: ‘Yes?’

EAF B: ‘Well… It has eaten some of the bottom hatch, this time, so… [inaudible].’

LF: (Mocking, in jest) ‘Has it now?… Well, then you just have to do that’.

What has happened is that the tapping hatch in the bottom of Furnace B had not been opened completely when charge #67B was tapped and that it has been ‘eaten’ (partially melted) by the melt streaming by. As a result, the first charge for Billet Casting will be delayed. But at the same time Billet Casting has also been delayed:

**Fragment 2.2 (15:28)**

BC: ‘We’ll be a little late over here.’

LF: ‘That’s all right. One of the furnaces has a hole in the bottom.’

While EAF B is being repaired and Billet Casting is preparing for the delayed billet casting sequence, the slab sequence is being finished. At 15:55, EAF B starts melting scrap for charge #69B. But then one of the electrodes on EAF B breaks and has to be replaced. Finally, at 17:49, charge #69B, the first charge for the billet sequence, is tapped and transferred to the Ladle Furnace for refinement and alloying.

At 18:30, the Ladle Furnace operator calls the crane driver over the radio:
Figure 17. The protocol for Product Type ‘S-23’. It specifies the composition of the alloy by listing the minimum, optimum (‘ideal’), and maximum analysis values for carbon, manganese, silicon, niobium; the minimum and maximum values for aluminum; and the maximum values for vanadium, nitrogen, titanium, and sulfur. (The unit is 10⁻⁵, i.e., the values for carbon are 0.122%, 0.135%, and 0.140% respectively). It also gives the minimum, optimum, and maximum values for the total carbon equivalent (Ceq) and the liquidus temperature for this alloy (1510 °C). It finally, in the next-to-last row, specifies that the delivery temperature from the Ladle Furnace should be 45 °C above liquidus for the first charge and 40 °C above for subsequent charges. (‘Udskrift af bestillingstyper’ (‘Printout of order types’), generated 4 July 1997)

Figure 18. The computerized control system at the Ladle Furnace, showing the primary screen: the matrix representation of the composition of the current charge. The columns represent (by row, for each component), the measured values, the stipulated values (minimum, ideal, and maximum), and the projected values based on the calculated effects of actions taken so far.
Figure 19. The protocol for processing steel for slabs at the Ladle Furnace. The timing of the procedure is, presumably, based on the calculations initially done by the Japanese steelworkers during the DDS delegation’s visit to Seiko Steel, Japan. The present diagram is a translated digital rendition of a handwritten diagram (‘Slabcharge på skeovn‘, or ‘Slab charge on Ladle Furnace‘), in a 10 page memo titled ‘Skeovn‘ (‘Ladle Furnace‘), dated 7 January 1986, authored by HEN.

Fragment 2.3 (18:30)
LF:    ‘J., I expect the next [charge] to go up [into The Tower] in 15 minutes.’
Crane driver:
     ‘Sure.’

The Ladle Furnace then calls Billet Casting:

Fragment 2.4 (18:45)
LF:    ‘We stick to a quarter to [i.e., 18:45].’
BC:    ‘That’s OK. We begin now.’
LF:    ‘That’s fine.’
At 18:45, the Ladle Furnace operator calls Billet Casting:

**Fragment 2.5 (18:45)**

LF: ‘Ladle Furnace here.’

BC: (Inaudible).

LF: ‘It’s 1560[°C], L. You may want to let it wait for a moment.’

BC: (Inaudible, but affirmative reply). (By 18:47, charge #69B is picked up by the crane and is on its way to Casting).

The series of mishaps encountered in starting this billet sequence is somewhat unusual, and so is the amount of talk required in launching the sequence. Normally, when the time to start a new casting sequence is approaching, the Ladle Furnace operator will call the Casting operators on the intercom and ask when they plan to start the next sequence. On the other hand, the Casting operators may also call the Ladle Furnace operator and inform her of their plans. Similarly, as we saw above, if casting of the new sequence is later postponed for some reason, the Ladle Furnace operator may be informed over the phone or the intercom. When a casting start is imminent, the Ladle Furnace operator may confirm that she is on time and perhaps check if they are indeed ready, as she does at 18:30 in Fragment 2.4 above.

6.2 Hand-over procedures

When the casting sequence has started, phone and intercom conversations will normally only take place if something quite unexpected has happened at one of the stations that may impact on the timing of the overall process. This is of course what happened in Fragment 2.1 above, at 15:15.

Apart from such routine troubles, charges are handed over with little or no talk. When the operator is satisfied that the desired temperature and quality has been achieved, a last sample is sent to the laboratory for analysis (for quality control purposes). Simultaneously, the Ladle Furnace operator will call the laboratory and state unceremoniously: ‘CaSi-test on 75’, meaning ‘This is the last analysis for charge number 75’. She will now also call the Casting operators on the intercom or the phone and, again, curtly say, for instance, ‘65 and ladle number 11’, meaning ‘The temperature of this charge is 1565 °C, and it’s in ladle number 11’, and at times perhaps just ‘52’, meaning ‘The temperature of this one is 1552 °C’. This breach of radio silence, as it were, is done for simple technical reasons: operators at the Casting do not have access to the temperature read-out from the ladle furnace.

That is, during a casting sequence, conversations with operators at other stations are quite unusual; they are as a rule restricted to actual or possible breakdowns that may interrupt the flow. If talk occurs at all, it is restricted to abrupt
handover messages stating the temperature of the charge and perhaps, for the records, its charge or ladle number. In fact, if the temperature is as it is supposed to be, the handover may not be accompanied by any talk at all. Only very little talk is required.

6.3 Conversation extraordinaire

It is not that the operators are not allowed to talk or are mute. For example, take what happened late in the afternoon in June when a billet casting sequence was planned to begin at 16:45 (Fragment 1). It is a very hot day and things are not running smoothly at all. The pyrometer is inaccurate, and argon stirring on one of the ladle cars does not work properly. Worse, the cooling water for the slabs casting machine is running hot, ‘disgustingly hot’, as it is expressed. Early in the afternoon, at 14:15, the cooling water is already at 45 °C, and when it reaches 50°, the machine will close down. A little later, at about 14:45, it is decided to interrupt slabs casting and quite exceptionally leave a charge in the ladle for later sequence of slabs. They are now all waiting for the scheduled billet casting sequence to begin. Tension is mounting, the phone in the Ladle Furnace control room starts ringing, and the operator replies:

LF:     ‘No, cool it! It’ll take another thirty minutes until the tundish is warm [pause, laughs]. Yes, sure… It’s all right.’

She hangs up, chuckling, explaining that it was one of the bosses who thought that the clock was already 16:45. But finally, at 16:45, the intercom message ‘CaSi test on 88’ announces that charge #88 is to be dispatched to Billet Casting, and two minutes later it is on its way:

LF:    ‘Ladle furnace here. 1572’
BC:    ‘Yes’.

But then things at the Ladle Furnace begins to unravel. The next charge had turned out to be high in phosphorous, and to refine it, oxygen blowing had been more extensive than usual; as a result its carbon content is low. But when carbon is added at the Ladle Furnace, it turns out that argon stirring does not work at all. The added carbon is just ‘dancing around on top’. To fix the fault the ladle is lifted out of the furnace for a (risky) visual inspection of its lower parts, but nothing untoward can be seen and it is put back. Suddenly, after 15–20 min of cursing and searching, the stirring begins again, for unknown reasons. But at this stage, there is only 20 tons left of the first charge, and Billet Casting needs this second charge without delay. It is prepared for dispatching: ‘CaSi on 89’, she says to Billet Casting, adding that ‘It may be a little low in carbon, but there’s nothing we can do about it’. The rationale behind this decision is that the alternative course of action would be to let the entire Steel Plant
wait unproductively for another three hours. Anyway, while CaSi is being rolled into
the charge, it is undergoing excessive stirring, and the slag suddenly looks ‘thin’, as it
should. As it is dispatched, Billet Casting calls over the intercom:

**Fragment 3.1 (17:00)**

BC: ‘How’s number two doing?’

LF: ‘Like shit. It’s on its way. But what you get, for
that I won’t guarantee. There was no bubbling
in the middle of it all. So there were twenty
minutes where I couldn’t work on it.’

BC: ‘[Inaudible] You don’t say!’

LF: ‘But apart from all the excuses, it’s on its
way. It’s 1561[°C].’

BC: ‘Which ladle is it in?’

LF: ‘Number 5.’

BC: ‘Thanks a lot.’

The Ladle Furnace operator then receives the final analysis results on the labo-
rary computer terminal and sees that the carbon content was within the norm
(18.4 points) and exclaims to the colleagues in the control room:

**Fragment 3.2 (17:02)**

LF operator:

‘Yes! We just know that kind of shit.’

LF assistant:

‘OK?’

LF operator:

‘Bullseye! Why are we making all that fuss?’

All laugh. The operator buzzes Billet Casting over the intercom:

LF: ‘Luck for fools!’

BC: ‘What?’

LF: ‘I say, luck for fools. The test is in and it’s OK.’

BC: ‘It’s amazing how lucky you are all the time.’

LF: ‘Exactly my point.’

These bursts of conversation are — again — quite extraordinary. They talk
here, not only because there is a short natural break in the flow of events, but
because there is something out of the ordinary to celebrate. If they had not made
it in time, the entire plant would have been stopped for many hours. A tense
period has ended in success. It was not a normal day.

On a normal day, by contrast, only little talk is heard. Apart from the short con-
vosations required to synchronize start-up procedures and the very abrupt exchanges
that sometime accompany handovers in the course of a production sequence (the curt,
often unanswered, utterances that simply state the ladle number and temperature of the next charge), work generally proceeds quietly. As noted above, it is not as if some sort of ‘radio silence’ has been decreed. There is no indication that operators have been told to ‘keep off the air’. I definitely did not observe any reluctance among steel workers to comment on management, crack jokes, banter, etc. It is rather that frequent or continual conversation about proceedings is not needed and for that reason probably would not be tolerated by the workers. At any rate, it would interfere with the cracking of jokes, the banter, the badinage, the gossip, and, occasionally, when things are quiet, the chance to relax, to unwind, to browse the tabloids.

6.4 Looking (and Listening) for trouble

Finally, the Ladle Furnace operator has on her console two half-duplex radio sets, one tuned to a radio channel shared by all crane drivers in the Steel Plant, and the other one tuned to the radio channel of the company’s central maintenance service. These radio sets are always on, but normally at low volume so that the exchanges and conversations on the channels are barely audible unless one is sitting in the chair by the console. The exchanges and conversations on the two channels thus become part of the background noise of the control room and they are monitored in much the same way: as long as everything sounds ‘normal’, operators do not pay particular attention to the chatter, but as soon as the tenor of it is out of the ordinary (e.g., somebody is referring to a disturbance or a breakdown) or something of import for one’s own work (e.g., an electric arc furnace operator asking ‘their’ crane driver to take a certain action, now), the Ladle Furnace operator will turn to the radio set, turn up the volume and listen attentively. From time to time she will join the conversation by making a comment:
‘The Discipline of Steel’: Technical Knowledge in the…

**Fragment 4**

1st crane driver:
‘How many more [charges] for the tower?’

2nd crane driver:
‘I don’t know.’

Ladle furnace operator (bends over and pushes the button on the radio set):
‘It would be great if the next one tapped by E. makes it.’

Similarly, after an agitated burst of talk on the maintenance radio channel, the Ladle Furnace operator calls Slab Casting (SC) over the intercom:

**Fragment 5**

LF: (In a teasing tone of voice) ‘Panic’s rising down there in adjustment, eh? I think the electrician is shouting somewhat.’

SC: (The reply is largely inaudible but the gist of it is that the equipment does not work properly).

LF: ‘Oh, that’s what the problem is.’

In the same manner the Ladle Furnace operator will scan for various disturbances that might upset operations and spoil the carefully accomplished but precarious continuity. On a hot day, for example, she will routinely check the cooling water temperature in the furnace control system, not only to determine the temperature of the cooling water at her end, at the Ladle Furnace, but also to determine the cooling water temperature at the casting machines, reasoning for instance, that when the temperature is 42°C at the Ladle Furnace, then it is 45°C at Slabs Casting. ‘When it reaches 50°C where he is [in The Tower’s cooling system], the machine closes down, and then he cannot cast anymore.’ Adding that, in the situation at hand, ‘It is not certain that we can make three more.’

Or when a charge has been dispatched to Casting and the ladle has passed in front of the window of the control room and has reached ‘The Tower’, she will briefly bend slightly across the console, look up, and check if the ladle can be opened. If it cannot, casting is interrupted.

That is, talk does occur between stations but the (inexorably) ‘sequential organization’ of these brief conversations does not ensure the overall coordination of the production of steel.

7 **Coordinative practices of the first order: geared into the world**

So, how do they do it?

Look at the instruments available to the Ladle Furnace operator in Figure 21. A video link to the hall housing the two electric arc furnaces gives the Ladle Furnace operators a bird’s eye view of the furnace shop (Figure 22). Since the
camera is placed high on the end wall, under the ceiling, the level of resolution is quite low, but the video link nonetheless enables the Ladle Furnace operators to detect exactly those events which are important for the temporal alignment of activities. A sudden increase in light intensity on the screen will make the operators look up to check what is happening. The glare may be caused by scrap being dumped into the furnace: the roof of the furnace is removed to allow the crane driver to dump the contents of the basket into the furnace, and flames, showers of sparks, and a lot of smoke are clearly visible. But the sudden glare may also be caused by slag being removed from one of the furnaces: the furnace is tilted backwards and slag is poured through the slag door into a slag pot. The trained eye can tell the difference between the two events, even in the poor video rendition, and in the case of a new basket being loaded the glare is often combined with booming sounds as well as vibrations in the walls and floor from crane movements and 50 or 60 tons of scrap being dumped into a furnace.

If the sudden glare is indeed caused by a new basket of scrap being dropped, the operator or her assistant will look up from the monitor to the clock on the wall to note the time. Sometimes one of them will say, for instance, ‘That was the second basket in furnace B’, especially if there has been uncertainty as to the exact schedule. Anyway, the operator will then mark the time of the event in the Production Report. (I will discuss the many roles of this report later). If the glare is caused by removal of slag, this is duly noted as well, since it is an indication of the state of the process: they may be getting ready to start tapping, or the charge may contain too much phosphorous.

Another source of insight into the state of the preceding processes is provided by data from laboratory analyses of the samples taken at the furnaces; these data are displayed on the same computer monitor on which the analysis data from samples taken at the Ladle Furnace are displayed. As they scroll by, the analysis data give the Ladle Furnace operator an opportunity, so to speak, to look over the shoulder of her colleagues in the EAF control room and determine how far the given charge is from being ready for tapping. However, for the purposes of the Ladle Furnace operator, only the values for phosphorous and manganese are noted, as the other ingredients (e.g., carbon, silicon, aluminum) may very well have been burnt off in the meantime.

The material work setting thus provides the Ladle Furnace operators with a rich repertoire of sources from which she may gather the state of the preceding processes. The sounds and vibrations of moving cranes and the shocks and bangs of scrap being dumped as well as the sudden glares on the video screen enable the operators to take notice of the time of the first and second baskets, the time of removal of slag, and the time of tapping; and the test results scrolling by on the computer display give the operator the temperature and composition of the current charges in the electric arc furnaces. Altogether, these signals and cues provide the Ladle Furnace operator and her assistant with a basis for assessing and re-assessing or calculating and re-calculating the temporal structure of the next few hours and, hence, for scheduling and re-scheduling their work.
As far as the subsequent processes are concerned, the Ladle Furnace operator has no direct access to monitoring the activities of her colleagues at Casting but she has a meter on the wall over the console (Figure 21) on which she can see how many tons of steel have been cast from the current charge, and, in the case of billet casting, how many molds are currently in operation. This rather crude indicator enables the Ladle Furnace operator to assess or calculate when the next charge must be ready for casting. Furthermore, she can (albeit with some difficulty when sitting in her chair) see ‘The Tower’ in which the ladle with liquid steel ready for casting is placed. If the operators at the casting machine for some reason encounter problems and have to discontinue casting (they may, for instance, not be able to open the hatch at the bottom of the ladle), they have to rotate the turntable 180°, which is visible to the Ladle Furnace operator through the window behind the console. Noticing this, she will get up from the chair to see better, swear under breath, call the Casting operators on the intercom to ask how serious the problem is, and then begin to reschedule her own work.

7.1 Making ends meet

On the basis of the wide variety of indicators of the state of the preceding and subsequent processes, the Ladle Furnace operator and her assistant engage in an intermittent but ongoing process of scheduling and re-scheduling. Sometimes the re-scheduling will take the form of a joint oral calculation exercise. Sometimes the Ladle Furnace operator will think aloud, letting her colleague overhear her reasoning, and sometimes he will provide information or opinions which may be relevant. Sometimes the two will discuss the schedule in the form of a brief conversation:

**Fragment 6**

Ladle furnace operator:

‘Is it the second basket now [on EAF B]?’

Ladle furnace assistant:

‘Yes.’

Ladle furnace operator (looks at the clock):

‘Then he’ll tap it at 17:00 hours.’

But most of the time, the ladle operator will just turn to her right and look at the ‘Production and Stoppage Report’ on the right-hand side of the console, do some calculations, and update the ‘report’.

This Production Report, which is to be filled in by the Ladle Furnace operators in the course of each of the three shifts, serves multiple function. The operators at the other stations have to produce similar reports. The Production Reports are collected every 24 hours and copied and distributed among supervisors, engineers, and managers.
horizontal axis and the different jobs, i.e., charges, on the vertical axis (see Figure 23). The time axis is divided into 24 columns, one for each hour in the report period (from 06:00 to 06:00), whereas the charge number and the product type number are entered by hand in the two left-hand columns. The handling of each charge is represented by a set of rectangles in the appropriate row. Each step in the process is marked by a vertical line indicating the time of the event. When the charge has been tapped and the ladle is waiting on the ladle car, a vertical line is entered to record the time of tapping and to indicate that the charge is now waiting. When it is moved to the waiting position of the ladle furnace, another line is entered to indicate that event. And so forth. The space between the two lines marking the time of tapping and the time of transfer to the Ladle Furnace is marked by a horizontal straight line (—) to indicate that the charge was waiting on the ladle car; likewise, waiting time at the Ladle Furnace is marked by a horizontal waved line (\(\sim\)), whereas processing time is marked by an \(\times\).

Now, in filling-in the Production Report for later use by management, the operator is producing a representation of the temporal order of the process that she can use in her own planning work as well. She will normally not wait until a charge has in fact been tapped to enter the vertical line denoting that it is now waiting on the ladle car but will make a tentative pencil mark that indicate when a given charge should be ready for tapping (based on, for instance, the time of the first and second basket) and, by extension, when it will transferred to the Ladle Furnace, and finally when it then is likely to be ready for casting; everything being equal, of course. When this tentative schedule, inscribed by pencil with a very light pressure, turns out to be in need of revision (e.g., the charge was tapped on time but had to wait longer than normal), she will fetch her eraser and change the tentative schedule with the pencil (very delicately). That is, what eventually becomes a Production and Stoppage Report is, while it is being constructed, also a dynamic production plan — a first-order incarnation of the plant’s third-order ordering system — that allows the operator to register, preserve, and visualize the salient temporal features of her work over the next few hours in a manner which is perfectly appropriate for the complexities of the production of steel: with a thin pencil mark and a big eraser.

7.2 Interacting in the causal nexus

‘the world is there to be consulted should we choose to do so. […] The situation of action is thus an inexhaustibly rich resource’.

Lucy Suchman (1987, p. 47)
While the Steel Plant to the unsuspecting visitor is a scene of infernal sights, noises, sensations, to the skilled worker it is an environment rich in resources. This is another crucial part of the answer to the question, how are they able to coordinate their distributed and quite contingent local parts of the overall, time-critical process?

When the crane is moving in the furnace shop, the floor of the Ladle Furnace control room vibrates noticeably, not unlike how it feels when standing on a platform when a train thunders by behind one’s back.. This perception may indicate events such as the next basket for one of the furnaces but also possibly the replacement of an electrode. When 50–75 tons of scrap falls into one of the furnaces some 30–50 m away, a tremor in the floor can be felt and a distinct thud can be heard, especially if it is EAF A, the closest one. Occasionally, especially during winter, there may be rainwater or snow or ice in between the scrap, which, when suddenly exposed to an environment at about 1600 °C, will cause an explosion of steam, leaving nobody in doubt that one of the furnaces has received another basket of scrap. When one of the electric arc furnaces is melting scrap, its electrodes immersed into and heating the steel by consuming 75 megawatt, a loud buzzing sound is the obvious signature. In fact, because EAF B is placed at a larger distance from the Ladle Furnace, its melting-ongoing buzz is less loud, and to the Ladle Furnace operator the difference in loudness of the buzz therefore identifies which furnace is currently doing its bit. At the same time, in the video monitor, significant events such as the removal of the roof of one of the furnaces, the blowing of oxygen into the melt, the pouring of slag into a slag pot, can be distinguished by the Ladle Furnace operator in the form of different patterns of light of varying intensity in the video image of the furnace shop. Similarly, intense light suddenly shining through the door at the remote end of the Ladle Furnace control room, behind the console, is an indication to the Ladle Furnace operator that steel is now being tapped. And so on.

The overwhelming presence of environmental cues is the firm basis of coordinative practices at the Steel Plant in general. It may for example be the case that the operator of EAF B needs to radio the driver of the furnace shop crane to ask him to have the next basket of scrap delivered, but not much talk is required; for if it is the first basket that is needed, for example, the crane driver will typically have noticed that slag was recently removed and steel tapped from that furnace; he will know that it is about time for the first basket and may even already have fetched the basket. In the same way, when preparing for tapping, the operator of EAF B may have to inform the ‘hole man’ that the charge is ready for tapping, but the ‘hole man’ will normally be ready for this anyway, as he will have seen that the charge has had slag removed and that the furnace has been tilted forwards, to the tapping position.

Again, the crane driver servicing the Ladle Furnace does not need to be told that a new charge has been tapped and is waiting on the ladle car. He can see that from his cockpit, just as he can see if the charge in the ladle is being purged by argon stirring. He can also see if the waiting position of the ladle furnace is
empty (in fact, he will normally know that, because he may himself have picked up the last charge and moved it to the tower). That is, he does not need to be asked to transport a ladle from the ladle car to the Ladle Furnace. Likewise, the crane driver can see that the ladle furnace has ‘rotated out’ and that a ladle is now being prepared for being dispatched to Casting: the CaSi line feeder is rattling and argon is ‘bubbling’. When the CaSi line feeder withdraws and argon stirring stops, the ladle can be picked up. And in the middle of a casting sequence, he will also know where to take it without being told; but at the end of the sequence, the Ladle Furnace operator will tell him, over the radio, that ‘This is the last for Slabs’ or that ‘This is the last for Billet Casting’, as the case may be.

To illustrate the point, the perceptual skills involved can be compared to driving a car on the motorway. What you see in front of you and behind you are vehicles. There are people in those cars but you normally do not see them, and their bodily conduct is normally not accessible to you. What is accessible is the behavior of the vehicles. You are for instance driving in the outermost (or faster) lane, overtaking a row of vehicles in the innermost lane. What you want to watch out for in that situation is whether any of those vehicles suddenly begins to veer out, into your lane. Not trusting that the drivers will look back and indicate before swinging out, you’ll be watching the speed of the vehicle relative to that of the other vehicles in that lane (is it closing the distance to the vehicle in front of it? how fast?) and the position of the vehicle relative to the lane (is it in the middle of its lane or on the outmost part of it?). The causal relationships between the features of the environment (lanes, vehicles, velocity, acceleration, relative position, direction) provide a rich resource for coordinated driving without recourse to symbolic communication (activating the indicators, flashing the headlights, honking, gesturing). The experienced driver has learned to ‘read’ the traffic, that is, learned to glean, from the dynamically changing configuration of the material setting, signals and cues of import for his or her own driving.

The point is this. Like all material objects — indeed, like every leaf that trembles, like every grain of sand — artifacts and structures are multifarious in their characteristics. Their properties can be enumerated endlessly. Material artifacts are persistent; they stay around; they acquire a history of use that remains there, readily available, at the surface, as traces of wear and tear, etc. They are also resilient to our aims and purposes; they are stubborn and opaque. Electric arc furnaces not only melt steel, they do so while at the same time emitting light, sparks, heat, vibrations, sounds, smoke, dirt, etc. Cranes not only relocate objects in abstract space; they make the floor tremble while doing so; they can be heard, they cast shadows, and their load features prominently in the visual field when passing by.

The evolving material setting is indeed ‘an inexhaustibly rich resource’ for skilled actors, as Lucy Suchman puts it (1987, p. 47). Exploiting it is an essential feature of skill that — Michael Polanyi’s ‘tacit knowledge’ proposition
notwithstanding — has often been described by workers in a reflective moment. For example, a pulp mill worker interviewed by Shoshana Zuboff recalls:

‘I used to listen to the sounds the boiler makes and know just how it was running. I could look at the fire in the furnace and tell by its color how it was burning. I knew what kinds of adjustments were needed by the shades of color I saw. A lot of the men also said that there were smells that told you different things about how it was running.’ (Zuboff 1988, p. 63).

Or to take another striking example from a quite different domain of skilled work, long-distance yachting. In 2005, Ellen MacArthur set the record for the fastest solo non-stop voyage around the world (less than 72 days). On her return she reflected on what enabled her to know at any time the state of her boat:

‘She [i.e., her boat] really does have a character. […] She does have a personality. She talks all the time. There’s always noise coming from the different foils. I can always hear the speed we’re doing; often, I don’t even have to look at the speed, I know when we drop below 15 knots of speed. […] It’s like a humming, going to a kind of whistling, it’s just very, very fine vibrations.’

Just like traditional steelworkers (to some extent) knew the temperature from seeing the color of the steel, MacArthur knew the speed of her boat from listening to the humming and whistling of the foils in the wind.

Now, to refocus on coordinative practices, to actors working together in a setting, i.e., interacting through a material field of work by inducing changes to that field of work, all these properties of artifacts and structures are, potentially, important sources of indications of what is going on, of what colleagues have been doing, are doing, could be doing, will be doing, and will surely not be doing. Thus the Electric Arc Furnace operators do not normally need to tell the Ladle Furnace operator that a new charge is on the way to her. She knows that already when she sees that it is being tapped, or at the latest when the ladle with the charge appears, large and dark, in the window behind her console. The same applies for interactions between the Ladle Furnace and Casting.

The short verbal exchanges that now and then do occur, intermittently and point-to-point, are effective because — precisely because — they are situated in a causal nexus, a vast array of practical-material interconnectedness that is readily available to members. The bursts of discourse are typically indispensable but should nevertheless be seen as local and temporary adjuncts to the practically

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effortless alignment and integration of the distributed activities that are accomplished by materially constituted coordinative practices: small bridges over the occasional creek and canyon in a vast and otherwise contiguous landscape.

That is, from the wealth of indicators in the setting, the Steel Plant operators (typically) immediately know — that is, without interpretation, reflection, etc. — what is going on at the other stations, because they know the metallurgy of steel quite well; they know the structure of the plant, the causal interdependencies, the operational constraints; they know the sequential ordering, the timing, and the dynamics of the various processes; and they know the typical local issues that may arise at the different stations and the concerns of their colleagues there. In other words, they know the drill, they anticipate the next occurrences, they are confident with what will happen next, and what will not happen.

In spite of the seemingly impoverished means of communication and coordination available to them, the Steel Plant workers are able to coordinate and integrate their local activities into a continuous process, not in spite of, but by virtue of their material interdependencies. They are able to align and mesh their distributed activities routinely, very simply because the state of affairs is readily available in the material environment, for those who know what to look for.
7.3 Making time

‘The whole world is just one big clock’

This is then our next question: How do they, here and now, at this very moment, without the globally regulating pulse from some command and control center, and in the midst of this cacophony of noises and vibrations, in this barrage of sparks, lights, and smoke — how do they know what they themselves have to do and when? How do the operators, when in the midst of it, know what to watch for?

Consider this short series of events. A little before 16:00, the floor of the Ladle Furnace control room trembles and shortly thereafter the light intensity in the bottom-left corner of the image on the video monitor increases significantly. Sitting in her chair by her control console, the Ladle Furnace operator looks up at the monitor, looks at the clock on the wall, which now shows 16:00, and makes

Figure 22. Video monitor in Ladle Furnace control room showing, *top left*, the two EAFs (EAF B at the front); *top right*, the roof of EAF B lifted; *bottom left*, slag being removed from EAF B; and *bottom right*, a hot slag pot.
### Figure 23

The ‘Production and Stoppage Report’ for the Ladle Furnace. The first column lists (in hand-writing) the charge numbers, the second column gives the Product Type. The following columns represent the 24 hours for the three 8-hours shifts (from 06:00 to 06:00). The right-most column gives the ladle numbers for the charge in question. — The hand-written annotations (around 17:00–19:00 hours) comment that argon bubbling is deficient (‘bad bubbling’).
thin vertical line in the production report at the vertical line representing 16:45. She may, for the benefit of her assistant or the ethnographer, say ‘That was the second basket in B’, meaning: ‘Furnace B has now received the second basket of scrap; he’s on time, and I’ll probably receive that charge, as expected, at 16:45’. That would anyway be the explanation she would give, if asked. These sequences of action can be observed continually, hour after hour, shift after shift, day after day. They are what at day in the control room looks like.

A specific kind of vibration in the floor is, to operators, an indication that the crane in the furnace shop behind the wall is moving. But the crane may be moving for any number of reasons; it may be bringing the second basket for EAF B, but it may also be moving to remove the roof of EAF A, or to remove a slag pot from the floor, or to replace a broken electrode. What the vibrations are taken to indicate is entirely contextual. In other words, in and of themselves the various occurrences (vibrations, sounds, lights, etc.) are ambiguous. How do actors know what these cues mean?

For the operators, a key to the required disambiguation, here and now, is that there is a significant temporal structure to steelmaking.

Although absolutely mundane, the Ladle Furnace operator’s actions incorporate her knowledge of the temporal properties of the processes: their sequence and duration. She knows that to produce one charge of molten steel of 110 tons the EAF must receive scrap iron in two rounds, since the furnace can only hold 75 tons of not yet melted scrap; she knows that when scrap is to be added to the furnace, the dome has to be lifted and the crane will move the basket with scrap to a position on top of the now exposed hearth and release the scrap through the bottom of the basket into the furnace; she knows that this operation produces vibrations in the floor and a characteristic increase in light intensity of a particular shape on the video monitor; she knows that the melting and initial refinement processes at the EAFs take about 30 min, and that the last stage of the process, marked by arrival of the second basket, takes about 45 min; she knows that if casting proceeds without disturbances, and given the particular dimension of slab being cast, the Casting operators will need the charge at 17:25; and she knows that this leaves her about 35 min for killing and alloying the steel. In short, she knows that she is on time.

Gilbert Ryle offers an analogy that quite well illustrates steel plant workers’ skilled perceptual orientation when engaged in a casting run, while in the midst of it. Asking, what is it for a person to know a tune, Ryle suggests that we would describe him as knowing the tune,

‘if, after hearing a bar or two, he expects those bars to follow which do follow; if he does not erroneously expect the previous bars to be repeated; if he detects omissions or errors in the performance; if, after the music has been switched off for a few moments, he expects it to resume about where it does resume; if,
K. Schmidt

when several people are whistling different tunes, he can pick out who is whis-
tling this tune; if he can beat time correctly; if he can accompany it by whistling
or humming it in time and tune, and so on indefinitely’ (Ryle 1949, p. 226).

However, this does not imply that we, when speaking of his expecting the
notes or bars which are due to follow, ‘require that he be actually thinking ahead’
(ibid.). Rather, it means that he be ‘hearing expected note after expected note’
and listening for what is ‘due to be heard’:

‘Roughly, to know how a tune goes is to have acquired a set of auditory
expectation propensities, and to recognise or follow a tune is to be hearing
expected note after expected note. And this does not entail the occurrence
of any other exercises of expectation than listening for what is being heard
and what is due to be heard.’ (ibid., pp. 228 f.).

In short,

‘He knows how it goes and he now hears the notes as the progress of that
tune. He hears them according to the recipe of the tune, in the sense that
what he hears is what he is listening for.’ (ibid., p. 227).

In the middle of producing and casting a sequence, in the thick of it, the timing
of action and interaction acquires paramount importance because all activities are
paced by the overriding concern of ensuring the continuity of casting. Here, when
the music is on, operators are attuned to what comes next and anticipate events to
occur at certain intervals. In fact, as intimated above, there is a distinctly rhythmic
order to the production of steel. Scrap is melted in two steps, basket for basket;
samples are taken at regular points in the refinement process; slag is removed; the
molten steel is tapped, charge by charge, now EAF A, now EAF B, now EAF A
again, etc.; and, following the same pulse, charges are taken from one station to the
next. It may not be jazz but is does have a beat. The vibration of the floor followed
by a thud is not merely an occurrence out of the blue from which the operator, after
consideration, might note that ‘That was the second basket in B’. The vibration
of the floor followed by a thud is anticipated at this point in time, because EAF
B started on the first basket 30 min ago, because the video monitor showed that
roof of EAF B had been removed prior to the thud, and so on. To the operators,
the distinctly rhythmic nature of the process is crucial to their routine coordination
because of the time-critical character of steel production. It is their pacemaker.

On closer inspection, then, it becomes clear that the indicators of the state of the
process available to the Ladle Furnace operator are understood with respect to and
in terms of one overriding parameter, namely that of timing. The varying light pat-
terns relayed by the video connection, the vibrations and tremors in the structure,
the buzzing sounds, etc. enable the operator to keep tabs on the timing of the major events in the preceding processes. The laboratory analysis display allows her to gather how far the EAF operators are in their work. The casting counter display tells her how much, or how little, time she has left for refining the charges at the Ladle Furnace. The operator is thus monitoring or scanning the environment for incidental or intended indications of the temporal state and progress of the preceding and subsequent processes. Under normal conditions these indicators are sufficient for her to be able to align and mesh her part of the overall process with the activities of her colleagues at their respective stations.

7.4 Methodological interlude: metallurgical perception

Perceiving ‘is exercising an acquired skill, or rather it embodies the exercise of an acquired skill.’
Gilbert Ryle (1956, p. 365)

Now, we are on treacherous ground here. When describing the status of skilled perception in these practices, we run the risk of crass intellectualization of the operators’ conduct and hence of category mistakes, of imputing hypothetical cognitive intermediaries such as ‘inferences’, ‘interpretations’, or ‘unconscious schemes’, where none are specifically called for. We are, for example, tempted to say, when describing the effortless ways in which operators typically are able to coordinate their individual activities with those of their colleagues, that they, from what they are able to perceive of the state of the field of work and the changes to it, ‘calculate’ what is going to happen or must happen next, or ‘infer’ the plans and intentions of colleagues, detect if colleagues are facing disturbances, etc.’ (Schmidt 1998; Schmidt and Simone 2000). But when using such language (‘detect’, ‘calculate’, ‘infer’), we presume, without warrant, some private and intermediate cognitive ‘process’ in the course of which ‘sense data’, presumably generated by the energy of incoming electromagnetic or kinetic waves, propagating through air or solids, are ‘interpreted’ so as to become or produce meaningful visual, auditory, or tactile experiences.

The language used here (‘detect’, ‘calculate’, ‘infer’) is ordinarily used in discourses describing emblematically intellectual activities such as philologists’ editing a collection of assorted fragments of a handwritten manuscript, or military commanders’ planning the course of a military campaign, or surgeons’ planning a heart operation, or astronomers’ considering new data from a neutron start in a galaxy far away. What is intimated is intellectual work with graphics and textual data and similar representational artifacts that are carefully collated and considered. What is implicitly pictured is a hidden scene where some putative cognitive function (a homunculus, really) has at its disposal an array of, presumably discrete, ‘sense data’, available in some unnamed medium, which are then arranged and compared, weighing possible alternative
interpretations, discounting for noise, making allowance for known and unknown unknowns, etc.

To describe what steelworkers do, when in the middle of things, as making ‘inferences’ is to abuse the word *inference*. We make inferences when we carefully consider facts and figures and draw conclusions on the wall, proceeding according to rules of deduction. We ordinarily use that term in discourses where facts are stated, considered, compared, etc. But when I, while driving my car, see an itinerant cyclist crossing the intersection for red, I do not make an inference like (1) there is an obstacle ahead, probably a cyclist, (2) I’m right now moving forward by 45 km/h, (3) if I continue at this speed I’ll most probably hit the cyclist, and (4) if I collide with him, he’ll probably be hurt (a lot). I do not, in this situation, make inferences: I brake, and honk angrily.

This intellectualist language does not leave room for, not to mention facilitate, an account that adequately describes the specific skills displayed by operators but rather suggests that operators are perpetually struggling to make sense: searching and detecting, calculating and making inferences.

Our temptation to presume some intermediate inferential process is a manifestation of what Ludwig Wittgenstein in a lecture at Cambridge in 1932–33 described as an urge to satisfy certain ‘norms of expression’: ‘Whenever we say that something must be the case we are using a norm of expression’ (Wittgenstein 1932–33, p. 16). When describing a practice, especially one that is not discursively organized and thus does not offer the analyst the requisite language, we are tempted to introduce hypothetical covert objects or processes such as ‘mutual awareness’, ‘tacit knowledge’, ‘shared mental models’, ‘unconscious schemes’ or ‘rules’, and similar pseudo-theoretical notions to account for the regular order of overt conduct. The ‘norm of expression’ of the social sciences suggests that some such intermediary ‘must be’ involved in the generation of social order. To come up with an explanation that has general application, a universal key, the dominant ‘norm of expression’ dictates that we must dig deeper to uncover the presumptive hidden mechanism. But when describing a practice, ‘nothing is hidden’ (Wittgenstein 1945–46, § 559). What makes us insist that there must be some intermediary, however occult, is our slipshod use of such categories of ordinary language. What is required, that is, is that we carefully consider the conceptual geography of the domain of language in which we move when describing and specifying practices. (See also Schmidt 2012a, 2018a, b).

However, we are in the fortunate situation that the very issue of giving an adequate description of skilled perception that is not discursively organized has been discussed thoroughly by Gilbert Ryle and others. Echoing Wittgenstein’s admonition, Ryle recommends that ‘we should mistrust these “musts”’ (1956, p. 358). For example, a child and a man, with equally good eyesight, may be looking at a particular word in the newspaper. The man may look up and say that the word ‘Edinburgh’ is misprinted, whereas the child may not detect the misprint but say only that he sees the word ‘Edinburgh’. We would not ordinarily insist that there ‘must’ have been intermediate process of interpretation, some imaginary consultation of
an occult English dictionary. The child fails to see the misprint that the man sees, because, we would ordinarily say, he is worse at spelling:

‘Why must [the man] have done any pondering, considering or putting two and two together? All that the argument up to date has shown is that if he had not previously learned to spell, he could not now recognise misprints at sight. But why must the exploitation of knowledge previously acquired take the form of pondering? We ponder when things are not obvious to us. But when previous training results in things being obvious at sight, which would not have been obvious without that training, why should we have to postulate a present piece of pondering to explain the immediate obviousness of the misprint?’ (Ryle 1956, p. 358).

In fact, Ryle argues,

‘to be able to detect and discriminate things by seeing, hearing, tasting, and smelling is to have got a certain amount of a specific skill or family of skills. In all cases alike there can be trained or untrained observers. To detect or discriminate something, whether by sight or touch, is to achieve something, namely, to find something out by the exercise of an acquired and perhaps deliberately trained skill’ (Ryle 1956, p. 353).

Our language for dealing with our perceptual orientation with the world is enormously varied. For visual experiences, for instance, we use verbs such as ‘to look for’”, ‘to look at’”, ‘to search’, ‘to glance’”, ‘to notice””, ‘to spot””, ‘catch sight of””, ‘to gaze’”, ‘to stare’”, ‘to see that’”, etc.” (cf. Coulter and Parsons 1990). However, in this rich lexicon, we ordinarily make a very clear distinction between ‘task verbs’ and ‘achievement verbs’ (Ryle 1949, pp. 149–153). Verbs like ‘to look’, ‘to watch’, ‘to search’, ‘to ponder’ are task words: they denote activities; that is, they have ‘genuine duration’ in that they have a starting point and an end-point in time (Wittgenstein 1945–48, §§ 71–83). By contrast, ‘The verb “to see” does not signify an experience, i.e. something that I go through, am engaged in. It does not signify a sub-stretch of my life-story’ (Ryle 1954, p. 96). Verbs like ‘to see’, ‘to discover’, ‘to find’, ‘to understand’ are rather achievement verbs; they designate that one has succeeded according to a certain criterion of success: ‘Do you see the ship?’, ‘No, I don’t’, ‘Look closer, it’s to the right of the lighthouse’, ‘Yes, now I see it.’ — Or ‘I saw you on the street this afternoon, but you didn’t say hello!’, ‘Really? ‘Yes. You went right by me and you even looked in my direction’, ‘I’ll be damned but I swear, I didn’t see you.’ In short, ‘finding out something by seeing or hearing is, so to speak, a success or victory in the game of exploring the world’ (Ryle 1956, p. 361).
Now, perception, like digestion, obviously involves a host of bodily processes, but unlike digestion, perception is, to quote Christoph Pfisterer’s discussion of Ryle’s analysis of the concept of perception, ‘an achievement with standards external to bodily happenings’. As opposed to sensations like pain, tickling, nausea, or exhaustion, they are not ‘something that individuals can decide upon privately’ (2015, pp. 157 f.). They are marks of certifiably competent conduct.

The philosopher of science Norwood Russell Hanson\(^{36}\) has developed this aspect of the Rylean analysis of perception concepts in ways that are quite pertinent for the issue at hand:

‘To see and hear something are activities as conceived of from the perspective of practices. The infant and the layman can see: they are not blind. But they cannot see what the physicist sees; they are blind to what he sees. We may not hear that the oboe is out of tune, though this will be painfully obvious to the trained musician. (Who, incidentally, will not hear the tones and interpret them as being out of tune, but will simply hear the oboe to be out of tune. We simply see what time it is; the surgeon simply sees a wound to be septic; the physicist sees the X-ray tube’s anode overheating.)’ (Hanson 1958, p. 17).

You may hear a high-pitched sound in the room but you cannot be said to *hear* a mosquito if you have not learned what animal that is and how it sounds. Steel plant operators do not ‘sense’ patterns of light and color or low-frequency buzzing sounds or vibrations in the floor and infer from that what may be going on; they see (and *hear* and *feel*) furnace roofs lifted, slag pots glowing, steel being tapped, oxygen being administered, slag rich on iron oxides, argon purging ongoing, electrodes engaging, cranes moving scrap and melt. The difference is conceptual: it is the difference between conceiving of activities as *mere behavior* and as a practice (Schmidt 2018a, b). The difference is that, as features of a normatively constituted type of activity, as features of a practice, *criteria of correctness* apply: the furnace roof is indeed lifted, that bright spot in the video display is indeed a hot slag pot, and so on.

A study by Catherine Kasbi and Maurice de Montmollin (1991) illustrates quite well the crucial importance of the conceptual distinction between ‘to look’ and ‘to see’ (and between ‘to listen’ and ‘to hear’, and so on). In their study, Kasbi and

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\(^{36}\) Hanson studied in Oxford under Ryle (Hanson 1958, p. ix; Lund 2010). Although he in turn had significant influence on Thomas Kuhn’s thinking (cf. Kuhn 1962; Chapter X), it would be a gross misunderstanding of his work to read it as a contribution to epistemology, e.g., as a precursor of post-positivism (Tibbetts and Johnston 1985). His work is rather a contribution to clarifying the conceptual grammar of reasoning about scientific practices, in an attempt to free observers and practitioners of science of epistemological hypochondria (on that, see Laudan 1996; Hacking 1999; Zammito 2004). Hanson’s later lectures on *Perception and Discovery* are worth consulting for a thorough critique of the conceptual troubles of neuroscience and perceptual psychology as manifested in, e.g., notions such as ‘sense data’ (1969). — For a systematic survey of the conceptual geography of the wilderness between neuroscience, perceptual psychology, and sociology of practical knowledge, see the work of Maxwell Bennett and Peter Hacker (2003).
Montmollin explored the impact of computerization of the control room design for a new generation of French nuclear power plants. In the particular type of power plant in question, two operators were required to perform the overall control of the operation of the plant. The plant is a highly integrated system, and the activities of the two operators are complementary and interdependent. As in other early control rooms of nuclear power plants, information on the state of the plant is displayed on panels that are several meters wide. Because of that, the operators have to move about in the room in order to monitor and regulate the performance of the plant. As they both work in the same room, each operator can easily observe the other’s moving around in the room, which in turn enables them to align their activities routinely and without interrupting each other. Now, although the operators can be said to monitor each other’s moving around in the room, it would be entirely misleading to say that it is the colleague’s bodily conduct *simpliciter* or his changing position and bodily orientation in space that is seen. Rather, it is the colleague’s changing position with respect to the control panels or, better, with respect to the structural and functional features of the plant as represented by the various control panels, that allows each of them to simply see what the other is doing. If a colleague is standing in front of a certain panel, that colleague is not seen as occupying a certain bodily stance at a certain location in space but as doing something specific in terms of nuclear power plant control practices such as, for example, opening a particular valve, starting an auxiliary pump, etc.

Competent actors do not (normally) see what their colleagues are doing as ‘bodily conduct’. It is of course possible to do so, and mimics, parodists, and imitators may make a living from it. One can also describe what another is doing as *bodily conduct*; but then one is viciously mocking what the person is doing, and when done well it is a powerful weapon against the rituals of the authorities. However, in the context of work in real-world settings, only a complete stranger to the setting, a Martian or a sociologist, would see actions as ‘bodily conduct’. Members do not. They see colleagues doing nuclear-power-plant activities, or air-traffic-control activities, or urban-transit-control activities, or surgery-activities, or patient-care-activities, or banking-activities, or steel-production activities. The ‘bodily conduct’ of colleagues is seen and recognized, not in terms of a generic schema, but in terms of members’ technical knowledge, the requirements of the practice in question, and the structural and dynamical properties of the field of work: in terms of what is to be done, what can be done, what should not be done, etc.

To say that operators ‘see’ patterns of light on the video monitor and ‘feel’ vibrations in the floor, that they correlate these ‘sense impressions’ with what they know about the temporal characteristics of steelmaking processes and about the current production plan, and that they then ‘infer’ that EAF B is now receiving the second basket — would, in the words of Ryle (1949, p. 213), be a ‘a logical howler’. Sure, the ethnographer, in his ignorance, may very well ‘see’ nothing but bewitching patterns of light, ‘hear’ nothing but bothering sounds, and ‘feel’ nothing but bewildering vibrations in the floor, and a novice entering the plant for the first time would also be overwhelmed
by the sights and sounds, ‘something like… it’s just like Dante’s hell’. But the skilled steelworker would ‘see’, ‘hear’, and ‘feel’ differently. Trained and experienced steel workers ‘see’, ‘hear’, and ‘feel’ competently. In sum, perception concepts are used for attributing and for claiming knowledge of the characteristics of the perceived object or process. They are predicated on normatively constituted activities, on practices.

However, ‘the relationship between seeing and the corpus of our knowledge […] is not a simple one’ (Hanson 1958, p. 20). Perception concepts are not merely used for the ability to identify individual objects and events with respect to their class and to do so correctly (‘Do you see the ship?’, ‘I hear a mosquito’, etc.). To say of an actor that he or she ‘sees’ something is to say that he or she knows that ‘were certain things done to objects before our eyes, other things would result’:

‘Seeing a bird in the sky involves seeing that it will not suddenly do vertical snap rolls; and this is more than marks [in] the retina. We could be wrong. But to see a bird, even momentarily, is to see it in all these connexions. As [John] Wisdom would say [(1946)], every perception involves an aetiology and a prognosis.’ (Hanson 1958, p. 21).

Hanson later elaborates this important point:

‘When the youngster says “lightning and thunder”, he probably means “flash and rumble”. Again, a lot may follow, but what follows for him is different from what follows for the meteorologist — for whom “lightning and thunder” probably means “electrical discharge and aerial disturbance”. […] The meteorologist says: “The noise originates near that cumulus cloud. In principle the cloud is an electrostatic generator. The ice crystals within it produce, by friction between themselves, electric charges, the separation of which leads to a concentration of positive charge in one region of the cloud and of negative charge in another. As charge separation proceeds, the field between these charged centres (or between one of them and the earth) grows. Finally, electrical breakdown of the air occurs; we see this as lightning. It leads to a partial vacuum in the atmosphere. Surrounding air rushes in. The result is a disturbance not unlike the breaking of a lamp bulb; we hear this as thunder.” […] Much more than normal vision is involved in seeing a flash as lightning, and in hearing a rumble as thunder.’ (Hanson 1958, pp. 60 f.).

Perception is, if not ‘theory-laden’ (Hanson 1958, p. 19) then certainly ‘concept-laden’. Such attribution is often indicated by using expression such as ‘seeing that’, ‘seeing what’, etc. In other words, “‘Seeing that’ threads knowledge into our seeing’ (Hanson 1958, p. 22). When the Ladle Furnace operator inspects the slag in the charge in the waiting position she is looking for the color of the slag. In that regard, she uses a technique that may seem reminiscent of the practices of traditional
steelmakers (only that they did not inspect slag on liquid steel). However, what the Ladle Furnace operator sees is not merely that the slag, for instance, is black; she sees that the slag, in this case, is rich in manganese or ferro oxides and that she has to add alumix (see Sect. 4.2 above). It is metallurgically enhanced vision: the operator knows what to look for and also what causes it and what it implies.

To recognize the occurrence of what one has learned to expect to occur is not a process or an activity. It surely involves physiological (neurological, hormonal, chemical, etc.) processes; but the very recognition is the criterion of skill, it certifies mastery of a normatively constituted practice: it is an achievement. To postulate a unobservable hypothetical process (‘inference’, ‘sensemaking’, ‘interpretation’, ‘information processing’, whatever) as a necessary intermediary (say, between photons hitting neurons in the retina and recognizing the photon emitting object as a slag pot or a furnace) does not do any work, other than to demonstrate that one is a faithful follower of (representational) fashion. It is performing a linguistic ceremony.

Intermediate activities may indeed take place. Whether they in fact do is an empirical question and there are criteria for determining that, in that there will be observable behavioral indications such as indecision, hesitancy, wavering, bewilderment, bafflement, faltering. And in fact, operators engage in the whole range of modalities of cognitive conduct. At times, they watch for or search for indications that a certain state obtains; at times, they unexpectedly notice certain occurrences and change their course of action; and at times, they simply notice that things are as they are expected to be and press on. At times, they are in doubt as to what the situation may be and stop and ponder what to do, and at other times there is no doubt as to what is to be done. But the observable fact is that the Ladle Furnace operator typically does not engage in making inferences. She does not, as it were, mentally traverse the vast, indeed infinite, web of actual and possible interdependencies and interactions (there is a flare of light in the top of the video display, after which there is a circular white spot where the flare was…), in order to determine that, say, EAF A is removing slag (hence the flare) into a slag pot (hence the white spot afterwards) and this could mean that they are getting ready to start tapping in a few minutes. She is typically not going through such inferences. In the thick of it, this is what she has been anticipating; this is what the occurrences for the last 75 min led her expect; and when it happens, it is normally simply and straightforwardly evident that this is what it is. She sees that EAF A is on time, or not on time, as the case may be.

Seeing a hot slag pot for what it is, in the context of metallurgic practices (in contrast to the practices of, say, environmental protection or recycling slag as fertilizer), may happen instantaneously and with certainty, or it may set in only after a moment of hesitation or doubt. But the seeing is in any event not an activity (as looking certainly is). Seeing is an achievement: it is normatively constituted. To say, ‘I can see the hot slag pot’, implies that one knows what a slag pot looks like and is able to identify it in the scenery, in an appropriate manner, and it also
implies that one knows the significance of the presence of the hot slag pot at this juncture in the meeting and casting process and also to be able to act accordingly.

That is, perceptual achievement concepts such as ‘to see’ (or ‘to hear’, etc.) are closely related to knowledge concepts such as ‘to know how’, ‘to know that’, ‘to know what’, ‘to know when’, in that they are predicated of knowing how things look (or sound, etc.), behave, and so on. To know something is not an experience (nor, of course, a mental state), although the mastery of whatever it is one knows may be associated with an experience (à la ‘I got it!’, ‘We’re the champions!’). By saying, ‘A knows x’, we’re not ascribing a psychological attribute to ‘A’ (like ‘He’s confident’, ‘He’s confused’). We are rather granting ‘A’ a specific kind of authority, namely, that of having a certifiable competence: to be able to give correct answers to questions about a certain topic, give satisfactory solutions to certain problems, perform a specific task adequately, etc., according to some specifiable criteria of success. Thus, to say that ‘A knows x’, is to perform a speech-act somewhat similar to that of writing a cheque, issuing a receipt, signing a contract, issuing a diploma, etc. When saying, ‘A knows x’, we’re granting ‘A’ a certain institutionally endorsed competence with respect to a class of tasks (with associated rights and obligations).

The Ladle Furnace operators recognize metallurgicall objects, structures, events, states, processes as metallurgically significant. They perceive that EAF B is on time or that EAF B is running late. Indeed, they perceive that they are on time, or have plenty of time, or may not quite be on time, or running late, or may be in trouble. In fact, contemplation is not required — most of the time.

The explanation for that accomplishment is that the steel plant workers have learned the recipe of the process and its rationale and have been through it countless times over the years; they know the sequence and the rhythm, they have acquired and developed subtle visual, auditory etc. expectations; they know what to look for and listen for; and they know and recognize the typical variations. Thus, under the discipline of steel, in the thick of it, the operators do not (normally) make inferences about the state of the process; they do not (normally) deduce what is to be done. The operator is able to heed the occurrences in the other shop and the timing of the process at large because of her deep knowledge of steel production, of the plant and its facilities, of the temporal order of the processes.

Our answer to the question ‘How are they able to know what is going on?’ does not need to invoke hypotheticals. The answer is similar to the sarcastic answer Wittgenstein gives to his insisting interlocutor: ‘How do I recognize that this colour is red?’ he is asked. To which he rudely replies, ‘One answer would be: “I have learnt English.”’ (Wittgenstein 1945–46, § 381). That is, the short answer to our question is that the steelmakers have acquired solid knowledge of the metallurgy of steel and the idiosyncrasies of the plant. The slightly longer answer is that the steel workers, in their local work as well as in coordinating their local activities with those of their colleagues at other stations, are firmly grounded in metallurgical knowledge that enables
them to monitor routinely for and to disambiguate the often equivocal indicators the environment presents.

The crux of the matter is that the Ladle Furnace operators are highly skilled steel workers. A career as a steel worker begins on the floor in jobs such as preparing ladles, taking samples, working as ‘hole man’ or ‘melter’. After some years, one may become crane driver, and only after that, one may become EAF operator and, ultimately, Ladle Furnace operator. Even then, it takes one or two years at the Ladle Furnace to become an proficient operator. As a result, the Ladle Furnace operator and other old hands are intimately familiar with virtually every aspect of the widely ramified operation and know every cranny of the plant quite well. When sitting in the Ladle Furnace control room, she knows the drill at the other stations as well.

8 Implications for design

What does this analysis imply in terms of design considerations?

As we have seen, steel operators do not perceive mere generic objects and processes (whatever that might mean); they perceive in metallurgical terms: they see recently-filled-slag-pots, and slag-rich-in-carbon, they hear CaSi-being-added and scrap-being-dumped, they feel the EAF crane bringing the second basket for EAF B, etc. And — this is the point — they not only perceive in metallurgical terms; they perceive that they are on time or are late. Their skilled perception is temporally oriented; that is, when they see a recently-filled-slag-pot, they see that EAF B is making ready for tapping: it is on time. In short, their overriding concern is that of timing and they orient to and heed categories of indicators relevant to timing.

However, this concern is not well supported by the existing ‘interfaces’. The work of making plans and protocols work in practice is made more complex by the idiosyncrasies of the design of the Ladle Furnace control room. The indicators provided by the existing design are not integrated and the operator has to register and integrate the information in real time, often based on very indirect and potentially ambiguous indicators:

First, the Ladle Furnace operators have no direct way of knowing the state of the melting and refining processes at the EAFs. The lab results for the EAFs scroll by on the display in the Ladle Furnace control room unstoppably; they cannot be retained. The data concerning the charges at the EAFs and the Ladle Furnace are moreover also mixed up with lab results from Casting and Adjustment concerning already cast charges. Consequently, the operator may miss the result from a particular crucial analysis, for instance if distracted by other events or while being outside the control room to inspect the slag on the charge in the waiting position. To compensate for means of direct monitoring of the progress of the processes at the EAF,
the operators resort to indirect indicators of the state as manifested in the sound and fury of the processes as rendered by shifting light patterns in the video display, by vibrations in the floor, and so on, that together, to the trained eye and ear, mark the background rhythm. The video display was installed shortly before the field work was performed, as an obvious sign that Ladle Furnace operators had had difficulties with keeping abreast with what was going on in the Furnace Shop. The patterns on the video display and the other incidental cues are efficient and essential in the present setup, but they are also ambiguous. For instance, removal of slag from an EAF, which normally indicates that the EAF is readying for tapping, could also indicate that the slag contains pollutants and that a new slag has to be generated. Direct means of monitoring the state of the processes at the two EAF would give the Ladle Furnace operator significantly better control of the timing of the overall process.

Second, laboratory results for the Ladle Furnace itself are indeed retained but only for the charge currently under treatment at the Ladle Furnace, not the previous charges that have already been cast as well as the charge currently being cast. In order to ensure that variations in composition from charge to charge in a casting sequence do not exceed the prescribed variation limit, the operators therefore, as the system is configured, have to remember the composition of these charges. The complexity of the job would be reduced markedly if the lab data concerning composition as well as the locally produced temperature measurements are retained and available upon request, and second, if the variation interval as determined by the preceding charges is ongoingly calculated and indicated in the control system display.

Third, the data concerning the state of the casting operation in the counter on the control room floor are given in tons of steel already cast for each charge. This is hardly a metallurgically meaningful measure. On the one hand, the amount of tons already cast is only informative if the operator remembers the size of the charge in question and therefore is able to perform the subtraction. On the other hand and in any event, what the operator is concerned with monitoring for is not primarily the weight of the charge but time, and the amount of steel remaining in the ladle is only an indirect, rough, and tentative measure of time, for the casting rate, and hence the time remaining, is, for slabs, a function of the dimension of the specific product being cast, its cross-section, or, for billets, the number of billet molds in operation. What the Ladle Furnace operator needs to know is the projected time remaining for the current charge in the tower to have been teemed into the tundish: How much time do I have left?

Fourth, the Ladle Furnace process control system (Figure 18) does provide a synoptic view of the analysis results for the current charge combined with the projected composition values at the time of tapping as well as the target (‘ideal’) composition, based on the mass of each of the various fluxes and alloying materials that have been added to the charge. This gives the operator an invaluable idea of how far she is from the target value and, by implication, how much time she has until the charge is ready for casting. It is, however, for the operator to assess, from that representation and
from the various other incidental cues, the amount of time remaining for the current charge to be ready for casting.

In short, in its present configuration, the Ladle Furnace control room offers only fragmented and indirect sources of information on the preceding and subsequent processes, and it offers no explicit representation of timing, that is, of the temporal order to be achieved and of the current state of affairs with respect to that order: Where are we in the overall process, according to the protocol? How much time do we have left for this charge? Is there enough time left? Will we be short on time when the next charge arrives? And so on.

What the present study suggests is that what is required to support operators more effectively in their coordinative effort is to make the relevant metallurgical calculi available to them, so that they, instead of being reduced to gleaning from all kinds of cues, have a unified representation of the overall process.

Thus, to illustrate the point, an obvious solution would be to integrate the coordinative protocols: the overall Production Plan and the production and stoppage report chart, in a representation of the state of the overall process, based on automatically updated data from the available sources in the plant:

- the progress of charges underway at EAF A and B (given, for example, as stages: starting up, melting first basket, melting second basket, removing slag);
- the composition of charges underway at EAF A and B, compared to target handover values;
- the projected time remaining until tapping for EAF A and B;
- the composition of current and subsequent charges underway at the Ladle Furnace, compared to target values for handover to Casting;
- the projected time remaining for refining and alloying the current and subsequent charge at the Ladle Furnace;
- the state of the current casting sequence in terms of time left;
- the projected time remaining for refining and alloying the current and subsequent charge at the Ladle Furnace compared to the projected time until required handover to Casting.

An actual design of the control system (i.e., the methods of harvesting data, the principles of visualization, etc.) is not the point here (the plant does not exist any longer, after all, and the issue is moot). The point is rather that the sort of analysis ventured in this study points to design considerations that are a far cry from the design considerations one would obtain from an analysis in terms of ‘sequential organization’ of interaction or ‘mutual awareness’, that is, in the form of, say, ‘media spaces’. To practitioners, coordinative practices are conceived of in terms of work-related categories, not in terms of turn-taking or bodily conduct. It is the technical content, not the social form, that work and the coordination of work are all about.
Similarly, if we instead of ‘human factors’ were to focus on the technical factors that work is all about, an entirely different design direction might reconsider the entire cooperative work arrangement that is now predicated on the need of the Ladle Furnace operator to be able to inspect the color and viscosity of the slag in charges directly, on the spot. If that constraint could be relaxed by the application of novel sensor technologies, control of the ladle furnace could be relocated to the control room of the two EAFs. These prospects are being explored in multiple directions, for instance in the form of remote real-time monitoring of the temperature of liquid steel (e.g., Dorčák and Terpák, 2006); monitoring of gas stirring of melted steel in ladle furnaces based on acoustic sensor arrays (e.g., Kadam 2021); monitoring of slag composition by infrared imaging (e.g., Strąkowski et al. 2018; Patra et al. 2019); or remote chemical element analysis by means of laser-induced plasma spectrometers (e.g., Cremers and Radziemski 2013; Pedarnig et al. 2021). (For an overview of the prospects of sensor-based process control in steel production, cf. e.g., Kano and Nakagawa 2008; Thomas et al., 2011). As this is becoming technically and economically feasible, this may reduce the distributedness of the whole operation significantly and thereby afford much more routine alignment between the melting, refinement, and alloying tasks as well as a higher level of automatic process control (cf., e.g., Deguchi 2011; Cui 2018). This would give rise to a cooperative work arrangement rather similar to that of the control room of a nuclear power plant or an oil refinery, which, in important ways, would reduce the coordinative complexity of the existing cooperative work arrangement.

9 Science and art in practice

By way of concluding, let me bring it all back home: How do the operators manage to produce quality steel at a high rate of continuous casting while working under conditions of severe constraints and contingencies? What are the conceptual and methodological implications, if any?

The ultimate answer to our research question is that contemporary steelmaking is a family of practices based on scientific metallurgy. That makes it a category of practice that is fundamentally different from traditional steelmaking practices.

Traditional steelmakers were coping with a process that was not understood in any strong sense of the word. They knew from what they, as apprentices, had learned from their masters, from what they had heard or observed themselves, and from their own experience — that if they did $x$ and $y$, the result would more often than not be $z$. They had no way of knowing the intermediate process, the mechanism that caused the input to give the desired output. It was a conceptual void that often, in the imagination, was populated by occult entities, perhaps as a useful mnemonic device, or with inspired analogies and poetic metaphors ('the pores'). Moreover, they had very little control of the chemical composition and amount of input materials, of $x$ and $y$, or of the temperature and other circumstances, just as they had very little control of timing.
What they relied on was basically a set of qualitative empirical associations. It was a set of recipes, at best, or simply little more than household remedies. And finally, they had very few ways of inspecting and assessing the quality of the result. In view of this, the astounding fact is that they managed to produce steel products of high quality and sometimes also beauty. The explanation is that they, like other artisans, possessed intellectual acuity and sensory astuteness, combined with ample time to discard unusable outcomes and then try again (and again). (On artisanal work, cf. Long 2001, 2011; Smith 2004, 2022; Smith and Schmidt 2007).

Scientific metallurgy has virtually eliminated the vast space of uncertainty that Ancient, Medieval, and even Modern steelmakers had to cope with: the chemical composition and microscopic structure of steel are now known, as are the thermodynamic characteristics of the casting process (and of subsequent processes of rolling, hardening, tempering, annealing, etc.). Consequently, the practices of the Steel Plant workers are radically different from the practices of steel masters of Ancient India or of Medieval and Early Modern Europe. They are, rather, practices that have crucial features in common with the practices of producing microprocessor chips in the semiconductor industry, of administering chemotherapy at an oncology clinic, or of controlling nuclear power generation: the work practices at the Steel Plant, and with those also the coordinative practices, are applications not only of a body of theory of a special kind but of a kind of theory that provides calculi and thus affords the generation of recipes, plans, and procedures that have known confidence intervals.

Traditional and contemporary steelmaking practices are practices constituted by very different ‘theories’, or rather, they are practices constituted by ‘theories’ of very a different kind and epistemic status and transmitted in radically different ways: on the one hand, empiricist accounts of experienced regularities expressed in (typically vague) qualitative terms, initially handed down orally, later expressed in tentative prose; on the other hand, an array of calculi based on a solid body of metallurgical knowledge expressed in scholarly literature and college textbooks. In short, they are incommensurate practices. Or rather, practices in two different senses.

The skills and the role of the Steel Plant operators are distinctly different from those of traditional steelmakers. Where traditional steelmakers had to rely on strictly empirical recipes coupled with their — often highly sophisticated — bodily sensibilities, contemporary steel plant operators work with a process that is designed on the basis of rigorous scientific theory and which thus can be and is precomputed. For example, the chemical composition and hand-over temperatures of the well over 200 steel products in the plant’s Product Type Catalogue are pre-calculated on the basis of the phase diagram as founded in solid-state physics and thermodynamics. The metallurgists doing the calculations underpinning the recipes do the calculations with known confidence intervals. Likewise, the timing of the secondary process at the Ladle Furnace has been calculated by the staff at the control system vendor (in Japan) and later verified back at the Steel Plant. Reflecting these calculations, the Ladle Furnace treatment protocol leaves a window of
three minutes for each charge. The overall Production Plan also reflects those calculations.

The steel workers at the Steel Plant are able to achieve continuous operation only on the basis of these and similar scientific and technical advances. The steelmakers are not metallurgists, of course, but an introduction to the main tenets of contemporary metallurgy is a basic part of their training and education at the plant. Moreover, the design of the steel plant is based on the advances in scientific metallurgy over the last century. They have at their disposal the ordering system comprising the Product Type Catalogue, the precomputed Ladle Furnace Process Protocol, the overall Production Plan, the laboratory reports, the temperature meter and the casting counters, the control system, and the production and stoppage reports. And even though this is not immediately available to the observer, we must also take into account the work that has gone into the design of the plant and the concomitant prescribed processes. The continuity of the steel production process at DDS is the joint accomplishment of the efforts (separated in time and space) of the metallurgists, the plant designers at the vendor firms, the plant engineers, and the operators.

Contemporary steelmakers, of course, still rely on using their perceptual faculties to, for instance, inspect the color and viscosity of the slag (as well as to register the changing state of affairs as can be gleaned from by light patterns, vibrations, etc.). And of course, when heeding the progress of previous and subsequent processes of the overall production, in the midst of the production of steel, they in general rely on virtually the entire sensory apparatus of the human body in assessing the state of the process, integrating visual, auditory, pallesthetic etc. experiences in producing an evolving sense of the progress of the process. In that regard they do not differ substantively from traditional steelmakers. That is, like traditional steelmakers, the Steel Plant operators master a highly evolved art. There is, however, the crucial difference that their art is an art based on scientific metallurgy.

It would be misleading, therefore, to conceive of the perceptual skills of the Steel Plant operators as somehow continuous with the perceptual skills of traditional steelmakers. It is misconceived to conceive of perception in isolation, in the abstract, separated from the manifold of practice. Perceptual skills are acquired skills, embedded in our practices. Or, to use an analogy, ‘Hunger is hunger; but hunger that is satisfied by cooked meat eaten with knife and fork is a different hunger than one that devours raw meat with the help of hands, nails and teeth’ (Marx 1857, p. 29). The perceptual skills employed by the Steel Plant workers are not a residual left over from earlier practices after the transformation of steel production on the basis of scientific metallurgy and the introduction of the computational control system and facilities of measurement and calculation, but a feature of their overall skills as constituted through their acquisition of metallurgical knowledge.

In conclusion, then, the work practices of operators are constituted by ‘theory’ in the form of metallurgical knowledge, their own as well as the knowledge embodied in the overall configuration of the plant, in the equipment, in the measurement
instruments, in the computational calculi used in the laboratory for producing and displaying data concerning charge composition, as well as in the plans and protocols derived from this knowledge. But the practical application of a theory, and of the derived plans and protocols, is inexorably contingent and hence a practice: the contingency of the process has to be taken into account at all times. In that regard, steelmaking is still an art, but again, it is an art embedded in and predicated on scientific metallurgy.

Appendix I: The study

The field work was conducted at the Danish Steel Works Ltd. (Det Danske Stålvalseværk A/S or DDS) in Frederiksværk, Denmark. DDS converted iron and steel scrap into quality steel, in the form of plates for shipbuilding, boilers, construction, in the form of merchant bars for structural steel, or, to a minor extent, in the form of carbon steel and special steel products. At DDS, the fieldwork focused on Steel Plant where the initial processes of melting, refinement, alloying, and casting take place. The subsequent processes of adjustment, cutting, normalization, rolling, etc. were not investigated.

The main part of the fieldwork was carried out, in intervals, from February 1997 to June 1998. After this relatively intense period, occasional field visits continued until March 2000. For the entire duration of the studies, I had very generously been issued an access permit to the Steel Plant and could come and go as I pleased. I also had the good fortune of being given several ‘guided tours’ of the plant and was later allowed to move freely about.

A first outline of the findings was drafted concurrently with the ongoing field work. However, because of relentless difficulties with developing an adequate analytic account of my findings and of its conceptual implications (and in part also due to life’s exigencies), I soon had to put the work aside. The writing was resumed in 2004, however, and resulted, in 2006, in a manuscript in which the descriptive analysis of my observations was fairly complete, while the conceptualization of the findings still amounted to little more than a bunch of fragmentary attempts. The descriptive analysis of the findings in the 2006 manuscript constitutes the body of the present text.

The main findings have been presented in invited lectures at the OECD Halden Reactor Project, Norway (1997); at the COTCOS project workshop on ‘Awareness’ in Cannes, May 1998; at the University of California, Irvine (2000); at King’s College London (2001); at the Technical University of Blekinge, Sweden (2001); at the University of Siegen, Germany (2009–11); at ECSCW Master Classes in 2011, 2015, and 2017; and in a keynote talk at the ‘Coordination is work’ conference at the University of Siegen in July 2017. A draft version of the central descriptive and analytic parts of the manuscript was circulated and used for teaching purposes in my CSCW courses at the IT University of Copenhagen from 2000 through 2007.
Since the whole point of the study was to investigate work practices, it was of paramount importance to develop a passable understanding of the technicalities. At my request, a few members of the staff were generous enough to give me crash courses on the basics of the metallurgical and other technical foundations of steel production, in one instance by using a white board, in another by instructing me, step by step, display by display, in the use of the computer-based control system.

The observational studies focused on the central processes of refining and alloying at the Ladle Furnace. This choice was justifiable, as the Ladle Furnace was the nexus of the whole operation. So, most of my time in the field was devoted to staying in the Ladle Furnace control room for whole shifts, typically sitting next to the operator at the control console. Some of these sessions were audio recorded, as were all interviews. On a few occasions, production series of about two hours were video recorded.

Copies of internal standard reports such as ‘fault reports’ and ‘production and stoppage reports’ were collected as best I could, altogether reports covering 207 days, from November 1996 to October 1997, 1,325 pages in total. In addition to serving as ‘exhibits’ that document members’ actions and comments, these reports have been invaluable in that they, because they are produced continually as workers’ reports to management about their work, have provided me with detailed data I would otherwise have missed, if for no other reason, simply due to the sometimes hectic pace of events, the many concurrently occurring processes and activities across the plant, the noise. The collection of reports gives — as a collection — a vivid impression of daily life at the plant, the routines, and the routine troubles.

Since the work practices of steelmaking cannot be understood without at least a cursory understanding of the metallurgy of steelmaking. I made systematic effort to collect and peruse technical documents produced by managers and workers at DDS for various purposes, such as teaching materials (e.g., tutorial articles and compendia), reference handbooks, and process and product specifications.

Introductory works on the metallurgy of steel and on the technologies of steel production were also consulted at the time of the field work (e.g., Dennis 1967; Street and Alexander 1968; Elliott 1973; Reynolds and Weidmann 1990; Llewellyn 1994). Later, I have benefitted greatly from a number of additional works on the theory and history of the metallurgy of steel in general (Smith 1962, 1964, 1968, 1988; Wertime 1962; Ohashi 1992; Cahn 2001; Verhoeven 2007; Callister and Rethwisch 2010; Smil 2016), on electric arc furnace steelmaking technology (Plöckinger and Eiterich, 1985; Jones et al. 1998; Madias 2014), on continuous casting technology (Bojčenko 1957; Gallagher and Old 1963; Wolf 1992; Okumura 1994; Tanner 1998; Louhenkilpi 2014), and on ladle furnace technology (Fruehan 1985; Szekely et al., 1989; Holappa 2014). — As the field work was done in Denmark, all field work data are of course in Danish. In my effort to report the study in English, these texts have been of invaluable help in my attempt to get the English metallurgical terminology right, as have a number of reference works on the metallurgy of steel (e.g., Brown 1998; Pohanish 2003).
### Appendix 2: Main alloying elements and their effects on steel properties.

**Table 1** Main alloying elements and their effects on steel properties as a function of content. (Source: The Steel Plant’s internal tutoring materials and Winkel’s articles, compiled).

<table>
<thead>
<tr>
<th>Alloying element</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Content/ tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (Al)</td>
<td>Deoxidizer</td>
<td>May cause clogging of small caliber molds. 0.025% during casting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Micro-alloying element: Increases tensile strength and ductility; binds nitrogen under normalization which causes fine-grained structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increases durability, resistance to fatigue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boron (B)</td>
<td>Increases tensile strength and hardenability significantly</td>
<td>Difficult to control in production process (reacts easily with nitrogen and oxygen)</td>
<td>0.003%</td>
</tr>
<tr>
<td></td>
<td>Increases weldability (allows low carbon content)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>Increases tensile strength and hardenability</td>
<td>Decreases ductility</td>
<td>0.3–0.5% / &lt; 0.01%</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>Great increase in corrosion resistance</td>
<td>Decreases weldability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increases tensile strength and hardenability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>Increases tensile strength, hardenability, and ductility</td>
<td>Increases brittleness with Mn &gt; 1.6%</td>
<td>Normally 0.6%; HT steel: 1.35%</td>
</tr>
<tr>
<td></td>
<td>Binds sulphur (MnS in solid steel is harmless)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deoxidizer during production (binds free oxygen in liquid steel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>Increases tensile strength and hardenability</td>
<td>Decreases weldability</td>
<td>≤ 1%</td>
</tr>
<tr>
<td></td>
<td>Increases ductility at subzero temperatures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increases resistance to corrosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niobium (Nb)</td>
<td>(Micro-alloying element)</td>
<td>High Nb content (c. 0.03%) causes loss of ductility. Rolled niobium steel can be extremely brittle (this can be neutralized through ‘normalization’)</td>
<td>0.02%</td>
</tr>
<tr>
<td></td>
<td>Increases tensile strength significantly (causes fine-grained structure during normalization)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good weldability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alloying element</td>
<td>Advantages</td>
<td>Disadvantages</td>
<td>Content/ tolerance</td>
</tr>
<tr>
<td>------------------</td>
<td>------------</td>
<td>--------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>Nitrides of aluminum or titanium (e.g., AlN₄) increases tensile strength and ductility (after normalization)</td>
<td>Dissolved free nitrogen reduces ductility</td>
<td>c. 0.009%</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>Increases strength and elasticity Deoxidizer Increases resistance to corrosion</td>
<td>With increasing content, increases probability of hydrogen fractures</td>
<td>Normally 0.15–0.4%; spring steel 2%</td>
</tr>
<tr>
<td>Sulphur (S)</td>
<td>MnS in steel makes it suitable for machining</td>
<td>Increases brittleness (&gt; 0.05%); reduces perpendicular shock resistance (&gt; 0.005%)</td>
<td>Normally &lt; 0.02%; plates for shipbuilding &lt; 0.005%</td>
</tr>
<tr>
<td>Titanium (Ti)</td>
<td>Similar to aluminum (weaker deoxidizer, better at binding nitrogen) Forms hard carbides</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vanadium (V)</td>
<td>Deoxidizer Increases tensile strength significantly (inhibits grain formation during normalization-Decreases weldability) Increases hardenability</td>
<td>Similar to niobium, but causes less brittleness in rolled steel</td>
<td></td>
</tr>
</tbody>
</table>
Acknowledgements

The generous hospitality of the Danish Steel Works Ltd. and its staff is gratefully acknowledged. I am especially indebted to Camilla Mortensen and Linda Christiansen for patiently introducing me to ‘the secrets of steel’. I also thank former shop steward Jørgen Andersen for giving an interview in 2006 as a result of which much of the historical background of the practices I had observed became much clearer to me.

The original field work was funded under a collaboration agreement between Risø National Laboratory, Denmark, and the OECD Halden Reactor Project, Norway. The head of my department at Risø, Leif Løvborg, played a central role in establishing the project. My Risø colleague Steen Weber conveyed the contact to the Danish Steel Works.

The research has subsequently been supported by the Commission of the European Union under the TMR COTCOS network; by the Danish National Centre for Multimedia Research under the Distributed Multimedia project; by the Danish National Research Councils under the DIWA project; by the Velux Foundation under the Computational Artifacts project; by the Department of Organization at the Copenhagen Business School, and by the University of Siegen, Germany.

The reviewers of the two submitted manuscript versions (November 2021 and November 2022) and the different editors on deck have contributed significantly to making the present final version far more accessible to readers, not least by forcing me to rethink and make far more explicit the research context out of which this research grew and to which it is meant to contribute — and thus to liberate it of the marks of the twenty years of conceptual birth pangs.

I am finally indebted to the following colleagues and friends who, after reading earlier versions of the manuscript or parts thereof, have made encouraging comments: Poul Andersson, Liam Bannon, Nils Frydensgaard, Christian Frankel, Irene Odgaard, and Ina Wagner.

Authors’ Contributions  Not applicable.

Funding  Open access funding provided by Copenhagen Business School. The original field work was funded under a collaboration agreement between Risø National Laboratory, Denmark, and the OECD Halden Reactor Project, Norway. The research has subsequently been supported by the Commission of the European Union under the TMR COTCOS network; by the Danish National Centre for Multimedia Research under the Distributed Multimedia project; by the Danish National Research Councils under the DIWA project; by the Velux Foundation under the Computational Artifacts project; and by the University of Siegen, Germany.

Data Availability  Not applicable.
Declarations

Competing Interests The authors declare no competing interests.

Ethical Approval

1. Project description (in Danish) sent to engineer Camilla Mortensen, DDS, 21 March 1997:

‘Formålet med den planlagte undersøgelse er at opnå en bedre forståelse af arbejde og samarbejde under tidsskritative betingelser. Formålet er altså ikke at bedømme enkeltpersoners indsats, men at opnå en bedre forståelse af, hvordan krævende arbejde koordineres under bestemte forhold, således at det er muligt at udvikle bedre styrmings- og kommunikationssystemer. Jeg vil således især fokusere på arbejdet og koordinatien i den løbende drift (kontrollrum og lign.) og samspilliet mellem den løbende produktion og vedligeholdelsen af anlægget.

Undersøgelsen vil indbefatte flere forskellige analyseeteknikker. Jeg vil primært blot observere, hvad der foregår. Det vil sige, at jeg vil være til stede og lejlighedsvis — når det kan gøres uden at forstyrre — vil spørge til ting, jeg ikke forstår, eller som jeg af andre grunde gerne vil vide mere om. Jeg vil derudover gerne have mulighed for at interviewe udvalgte medarbejde fra forskellige funktioner (i størrelsesorden denen 6-7 personer) om deres arbejde. Hvert interview vil tage 1-2 timer og kan placeres på tidspunkter, hvor det ikke er til stor gene. Derudover vil jeg gerne have adgang til relevant skriftligt materiale (arbejdsplaner, fejlrapporter, tidsskemaer osv.). Endelig vil jeg gerne have mulighed for at lave kortere videooptagelser til analyseformål samt fotos til at understøtte formidlingen.

Resultaterne vil blive publiceret i videnskabelige artikler og rapporter. Det siger sig selv, men skal for en ordens skyld alligevel understreges, at resultaterne vil blive behandlet med en høj grad af fortrolighed. Observerede handlinger og udsagn vil blive anonymiseret, så man ikke vil kunne identificere enkeltpersoner.’

2. Information letter (in Danish) to staff at the Steel Plant, posted 14 April 1997:

‘Arbejdsanalyse på Det Danske Stålvalseværk

Formålet med undersøgelsen er at opnå en bedre forståelse af, hvordan arbejde under vanskelige betingelser koordineres. Jeg vil især se på samspilliet mellem den løbende produktion og vedligeholdelsen. Det videre sigte er at udvikle bedre styrings- og kommunikationssystemer.

Jeg vil primært blot observere, hvad der foregår. I denne sammenhæng vil jeg lave nogle kortere videooptagelser. Jeg ville gerne have adgang til relevant skriftligt materiale (arbejdsplaner, fejlrapporter, tidsskemaer osv.). Endelig vil jeg gerne have mulighed for at lave kortere videooptagelser til analyseformål samt fotos til at understøtte formidlingen.


Med venlig hilsen
Kjeld Schmidt’

3. Quoted informants were given the manuscript as it was being finished in 2021-22. Former shop steward Jørgen Andersen replied (in Danish)::

‘Jeg skal hilse fra [Skeovnsoperatør] - hun er jo ikke imponeret over dit arbejdstempo, men jeg har fortalt hende, at det var nok til at blive professor.’

[In English: ‘Greetings from [Ladle Furnace operator] – she’s not impressed with your work pace, but I told her that it was sufficient to become professor’].

Conflicts of interests No conflicts of interest to be declared.

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‘Periodiske system’


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Emne 3: Smeltning’ [‘Melting’], by Jan Tyberg Jensen.
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