Smart Maintenance: a research agenda for industrial maintenance management

Citation for the original published paper (version of record):
Bokrantz, J., Skoogh, A., Berlin, C. et al (2020). Smart Maintenance: a research agenda for industrial maintenance management. International Journal of Production Economics, 224.
http://dx.doi.org/10.1016/j.ijpe.2019.107547

ARTICLE IN PRESS

Int. J. Production Economics xxx (xxxx) xxx

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: http://www.elsevier.com/locate/ijpe

Smart Maintenance: a research agenda for industrial maintenance management

Jon Bokrantz [a,*], Anders Skoogh [a], Cecilia Berlin [a], Thorsten Wuest [b], Johan Stahre [a]

[a] Chalmers University of Technology, Department of Industrial and Materials Science, Division of Production Systems, SE-41265 Gothenburg, Sweden
[b] West Virginia University, Industrial and Management Systems Engineering, Morgantown, MW, 26506-6070, USA

ARTICLE INFO

Keywords:
Maintenance
Manufacturing
Industrial organization
Digitalization
Industry 4.0
Smart manufacturing

ABSTRACT

How do modernized maintenance operations, often referred to as "Smart Maintenance", impact the performance of manufacturing plants? This question is a pressing challenge for practitioners and scholars in industrial maintenance management, in direct response to the transition to an industrial environment with pervasive digital technologies. This paper is the second part of a two-paper series. We present an empirically grounded research agenda that reflects the heterogeneity in industrial adoption and performance of Smart Maintenance. Focus groups and interviews with more than 110 experts from over 20 different firms were used to identify contingencies, responses, and performance implications of Smart Maintenance. The findings were transformed into a contingency model, providing the basis for a research agenda consisting of five principal areas: (1) environmental contingencies; (2) institutional isomorphism; (3) implementation issues related to change, investments and interfaces; (4) the four dimensions of Smart Maintenance; and (5) performance implications at the plant and firm level. The agenda can guide the field of industrial maintenance management to move from exploratory work to confirmatory work, studying the validity of the proposed concepts as well as the magnitude and direction of their relationships. This will ultimately help scholars and practitioners answer how Smart Maintenance can impact industrial performance.

1. Introduction

The manufacturing industry is undergoing major change, triggered by the rapid advancement of digital technologies and a reduction in technology associated costs (Monostori et al., 2016; Thoben et al., 2017). Correspondingly, intensive research efforts are focused on uncovering adoption patterns and performance outcomes of manufacturing plants in 'Industry 4.0' (Dalenogare et al., 2018; Frank et al., 2019; Tortorella et al., 2020). Within manufacturing plants, maintenance functions are also doing their best to respond to this change. For example, in order to improve productivity whilst at the same time reduce maintenance costs, they are trying to implement new technologies and invest in new skills (Roy et al., 2016; Weiss et al., 2016; Chekurov et al., 2018). However, decision makers and practicing managers within industrial maintenance struggle with defining and/or agreeing on the goals of this change. Further, even if the goals were to be defined, the means by which they can be achieved are not well understood. At the same time, there is a lack of relevant and actionable scholarly guidance that support practitioners (Bokrantz et al., 2017). To this end, the first part of this two-paper series, Bokrantz et al. (2019) parsimonious conceptualization of "Smart Maintenance" embraces this problem and aims to provide useful, understandable and inspiring concept clarity to practitioners.

However, considering this situation from the broadest of perspectives, the scholarly field of industrial maintenance management should ask itself the question: what is our role in this major change? Given the adaptive role of science in society, scholars hold the responsibility of generating and disseminating useful knowledge that transforms social order (Corley and Gioia, 2011). This means that scholars are not distant bystanders for the purpose of theoretical explanations. Scholars must actively contribute to change by making their voices heard and solving practical challenges (Holmström et al., 2009). In other words, our role is to inform policy and practice (Antonakis, 2017). Success in this role hinges on research that is both relevant and rigorous, yet this is not a trade-off (Vermeulen, 2005). Relevance is ensured at the onset of the research by asking the right questions, not by ex-post translation of the

* Corresponding author.
E-mail addresses: jon.bokrantz@chalmers.se (J. Bokrantz), anders.skoogh@chalmers.se (A. Skoogh), cecilia.berlin@chalmers.se (C. Berlin), thwuest@mail.wvu.edu (T. Wuest), johan.stahre@chalmers.se (J. Stahre).

https://doi.org/10.1016/j.ijpe.2019.107547
Received 19 February 2019; Received in revised form 28 October 2019; Accepted 29 October 2019
Available online 1 November 2019

results into the language of practitioners (Corley and Gioia, 2011). When relevance has been established as an initial condition, the path forward is rigor. Research that progresses without rigor loses its relevance in the making. In ideal terms, causal effects are what the field should strive for and take as inspiration. The ultimate source for societal prescription is a clearly identified causal relationship with the mechanism explained (Antonakis et al., 2010). Therefore, relevant and rigorous empirical research plays a key role in informing policy and practice, and causal inference has been called for within maintenance research (Tsang, 2000). However, empirical research remain scarce within industrial maintenance management (Fraser et al., 2015), limiting the ability for scholars and practitioners to answer the general question: *if a plant implements Smart Maintenance, will performance improve?* This scarcity may be due to empirical research requiring significant financial and time resources; has high perceived risk; or that maintenance scholars are less familiar with the dominant research mode of the social sciences (Flynn et al., 1990). At the same time, formulating ideal goals to advance the maturity of a scholarly field is comparably easy, achieving them is much more difficult. However, establishing a clear vision is always a good place to start.

Our vision that guides the present research is to advance the maturity of empirical research within the scholarly field of industrial maintenance management. To this end, the aim of this paper is to outline a research agenda for Smart Maintenance. To form this agenda, we use an inductive, empirical research approach with over 110 participants from more than 20 different Swedish firms. By collaborating closely with practitioners, we discover important conceptual variables and the overall pattern of plausible causal relationships that can be empirically tested. In order words, establishing relevance and forming the path for rigor. The agenda thereby charts a new direction for maintenance research that can ultimately help scholars and practitioners answer how Smart Maintenance impact performance. The agenda also serves as a holistic blueprint for industrial managers when designing long-term maintenance strategies. If maintenance scholars invest in cumulative research efforts within this agenda, we believe that the field will be in a strong position to fulfil its role in society by enabling more economically, socially and environmentally sustainable production systems. Fig. 1 illustrates the structure of the paper.

We first reason for the general need of empirical research as well as outlining our own ideas of what is needed and how it should be done (Section 2), followed by summarizing our research methodology (Section 3). We then present empirical findings of important conceptual variables and plausible causal relationships that form our research agenda (Section 4). Finally, we summarize the study in our final discussions (Section 5) followed by presenting our conclusions (Section 6).

2. Empirical research in industrial maintenance management

There is a general lack of empirical research within the field of maintenance. When Fraser et al. (2015) reviewed the literature, they found that out of several thousand articles on the most common maintenance concepts, only 82 displayed empirical real-world evidence. In contrast, the primary interest of maintenance scholars is clearly reflected in contemporary literature: leveraging technological advancements. For example, Ruschel et al. (2017) reviewed over 150 articles aimed at developing technical methods and tools for industrial maintenance decision-making. Roy et al. (2016) reviewed close to 200 articles and mapped recent technological challenges in maintenance. Lee et al. (2014) gave an introductory summary to maintenance techniques for prognostics by citing the use of over 100 different types of algorithms. In light of this distribution of work and in a relative sense to the maintenance field as a whole, the amount of available empirical research is miniscule.

However, while there is a clear lack of empirical studies in the field of maintenance, this does not mean that there is none. There are plenty of examples of excellent empirical maintenance research available. To name a few, Mckone et al. (1999) defined a theoretical framework of Total Productive Maintenance (TPM), followed by empirically testing how contextual factors encompassing environmental, organizational and managerial issues influence the pursuit of TPM practices. Jonsson (2000) theorized about the importance of prevention, hard maintenance integration and soft maintenance integration, followed by linking empirical taxonomies of plants to contextual factors and performance differentials. Swanson (2001) linked differences in the use of preventive, predictive and aggressive maintenance strategies to performance, as well as showed that computerized maintenance management systems, preventive and predictive maintenance systems, coordination and increased workforce size, are effective means to cope with environmental complexity (Swanson, 2003). More recently, Aboelmaged (2014) empirically found that manufacturing plants are in better positions to adopt digital technologies within maintenance when they possess certain organizational characteristics. To advance empirical research within maintenance, Fraser et al. (2015) postulated a list of suggestions. This list included for example greater emphasis on phenomenon-driven research aligned with the interest of practitioners, training of academics in practical thinking, as well as reading more empirical literature (p. 655–656). We wholeheartedly agree with these statements. In addition, we believe that the formulation of a research agenda will act as a complementary and possibly even richer tool for stimulating an overall increase in empirical research. Therefore, we outline our ideas for what is needed and how it should be done in the following.

With respect to *what is needed*, our ideas rest on the premise that there are a set of basic research questions that encompass the majority of relevant empirical inquiries. First, there is one general question that unifies empirical scholars and practitioners within industrial maintenance management: *if a plant does X, will performance improve*? (Ketokivi and Mcintosh, 2017). This has been at the heart of empirical scholarship within manufacturing for decades and is the foundation for managerial prescription (Flynn et al., 1990; Ketokivi, 2016). Fundamentally, this question rests on the basic premise of *heterogeneity* (Bromiley and Rau, 2016). Without the scientific jargon: *differences*. Everywhere we look, we see differences between plants; in the technology that they use, the people that they employ, and the processes that they execute. This premise of heterogeneity gives rise to two basic empirical questions: (1) *Why is this?* and (2) *What are the implications?* (Ketokivi, 2016). These two questions aim to uncover the origins of differences with respect to *how,* and *how well*, plants do things (Englmaier et al., 2018). Expressed in more scientific terminology: persistent and independent heterogeneity in both practices and performance. Here, we mean practices in the broadest sense of the word (encompassing e.g., structures, resources, activities, capabilities). One origin of differences in the use of certain practices that has strong practical relevance is implementation issues.

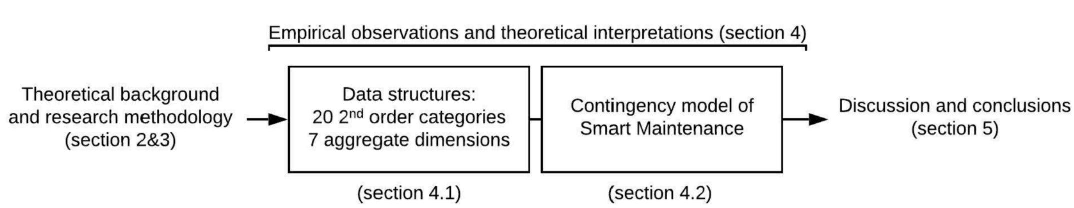

Fig. 1. Structure of the paper.

Plants differ in their use of practices because implementing them are both challenging and costly. The two forms of heterogeneity need to be linked with each other. Empirically, this translates to answering both how presence of certain practices ensure performance to exists (sufficiency), as well as how absence of certain practices prevent performance to exists (necessity) (Dul et al., 2010).

With respect to *how it should be done*, our ideas rest on the premise that we need both pluralism and unification. In organizational terms, both differentiation and integration (Lawrence and Lorsch, 1967). With pluralism, we mean different theoretical perspectives (e.g. strategic, organizational or economic) as well as methodological approaches (e.g. both qualitative and quantitative). With unification, we mean that independent scholarly efforts contribute to a common system-level goal: informing policy and practice through empirical research. In order to inspire maintenance scholars to pursue this common goal, we put our money where our mouths are, implement our ideas, and outline an agenda for empirical research within industrial maintenance management. Since empirical maintenance research must be grounded in problems that are relevant to practice (Fraser et al., 2015), the logical starting point is to draw from the real world and the experience of working professionals. At this stage, it is most useful to discover important conceptual variables and the overall pattern of plausible causal relationships that can be empirically tested (Antonakis, 2017).

We approach this through *theoretical prescience*: 'the process of discerning or anticipating what we need to know and, equally important, of influencing the intellectual framing and dialogue about what we need to know.' (Corley and Gioia, 2011) (p. 13). The basis for forming our research agenda comes from a large-scale qualitative study aimed at identifying contingencies, responses and performance implications of "Smart Maintenance". The first part of this study consisted of empirical observations and theoretical interpretations that served as the basis for conceptualizing Smart Maintenance and its four underlying dimensions as a configural organizational design (Bokrantz et al., 2019). This included a conceptual definition of *Smart Maintenance* as 'an organizational design for managing maintenance of manufacturing plants in environments with pervasive digital technologies', as well as definitions for the four underlying dimensions of *data-driven decision-making, human capital resource, internal integration*, and *external integration*. In this paper, we report the second part of this study in the form of empirical data and theoretical interpretations that we use to form our proposed research agenda. The focus of this agenda is to explain heterogeneity in the achievement of the four dimensions and linking this to performance heterogeneity. This paper should therefore be considered a direct continuation of the preceding one (Bokrantz et al., 2019).

3. Methodology

The overall design and implementation of the large-scale qualitative study are extensively and transparently reported in the first paper (Bokrantz et al., 2019). Therefore, in this second paper, we briefly summarize the key methodological steps of the study (Section 3.1), whilst encouraging interested readers to take note of the details within the preceding paper. Here, we give more weight to transparently disclosing our underlying reasoning for the approach we used to discover conceptual variables and the overall pattern of relationships (Section 3.2).

3.1. Summary of research design and research methods

The study was executed as a series of 14 focus group sessions and 4 interviews. A total of 113 individuals representing 22 different firms participated, of which the vast majority were practitioners. The focus groups were structured around the following three questions:

- (Q1) *When you think of Smart Maintenance – what attributes comes to mind?*
- (Q2) *What are the consequences of Smart Maintenance?*
- (Q3) *What does absence of Smart Maintenance mean?*

During the focus groups, data was collected using the web-based platform "Mentimeter" (www.mentimeter.com) in the form of anonymously submitted free-text answers, followed by group discussions. The interviews were semi-structured with flexible interview protocols. In total, the collected qualitative data consisted of 2410 Mentimeter entries and 179 single-spaced pages of transcripts. The data were imported into the qualitative data management software Nvivo (v. 11.4.1).

The data analysis was aimed at qualitatively building data structures, and consisted of systematic coding of 1st and 2nd order codes as well as aggregate dimensions (Gioia et al., 2013). The 1st order data reflected in-vivo informant quotes, and the 2nd order codes and aggregate dimensions reflected theory-centric interpretations. Data collection and data analysis were implemented as a cyclic process that continued until saturation was achieved at the 2nd order category level (Suddaby, 2006). To increase the trustworthiness of our data and assess the reproducibility of our coding, we iterated three techniques for external audits: peer-debriefing, member checking and intercoder agreement (Creswell and Miller, 2000; Corley and Gioia, 2004; Tracy, 2010; Campbell et al., 2013). The tentative and final analyses were discussed with both research colleagues at the authors' department (peer-debriefing) and industrial managers (member checking). Further, intercoder agreement was checked by having an external researcher code several random data excerpts and examining the degree of matching interpretations.

3.2. Contingency modeling

Consistent with our ideas of pluralism, we complemented our main theoretical foundation of contingency theory with alternative forms of fit (Sousa and Voss, 2008). We therefore incorporated multiple general theories to reconcile with the empirical context. Specifically, these were theories of Adjustment Costs and Complementarities (Milgrom and Roberts, 1995), Transaction Cost Economics (TCE) (Williamson, 1975), Skill-Biased Technological Change (SBTC) (Goldin and Katz, 1998) and Institutional theory (Dimaggio and Powell, 1983; Haunschild and Miner, 1997). Consistent with our ideas of unification, we integrated each of these theoretical perspectives to a unified whole with contingency theory as the foundation (Sousa and Voss, 2008). Contingency research focuses on fit amongst three types of variables: context, response and performance. The context variables are contingencies that are exogenous to the organization; the response variables are the organizational actions taken in response to contingencies; and performance variables are the dependent variables that represent effectiveness in the fit between contingencies and responses (Sousa and Voss, 2008). In the first paper of this two-paper series, we focused on the internal fit of the response variables (the four dimensions of Smart Maintenance), taking the environmental contingencies as given. Here, we instead take the response variables as given and focus on uncovering context and performance variables. Together, our findings form a complete contingency model. In Fig. 2, we schematically illustrate the resultant contingency model and its five perspectives, reflected in the underlying boxes and arrows. The numbers in Fig. 2 indicate different relationships, referred to in this paper as cases.

We populated the model using the following rationale, where the four dimensions of the Smart Maintenance concept were assumed to constitute the response variables. In cases 1–2, we treated the response variables as endogenous and focused on uncovering contextual factors influencing adoption, without considering performance relationships. The contextual factors could be external or internal, e.g. environmental contingencies or implementation issues. Both are sources of exogenous variation in the degree to which we are likely to observe the adoption of Smart Maintenance. We derived the contextual factors using two perspectives: selection and system. *Selection* (Case 1) focused on how single

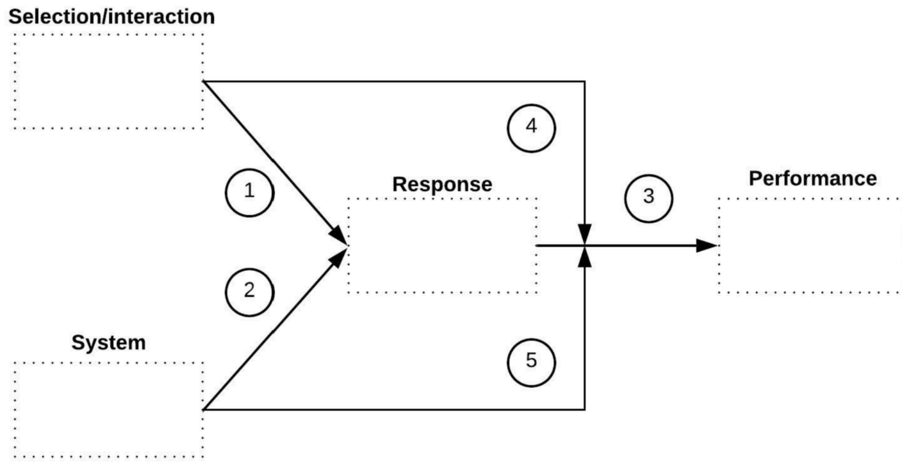

Fig. 2. Schematic illustration of the contingency model.

contextual factors affect single response variables, and *system* (Case 2) focused on how bundles of contextual factors affect bundles of response variables. In cases 3–5, we treated the response variables as exogenous and focused on performance relationships using three perspectives: direct, interaction and system. *Direct* (Case 3) focused on direct effects of response variables on performance, *interaction* (Case 4) focused on interaction of pairs of contextual factors and response variables which affects performance, and *system* (Case 5) focused on internal consistency of bundles of contextual factors and bundles of response variables that affect performance (Sousa and Voss, 2008). Since no relationships were tested in this study, we focused on the overall pattern of variables and acknowledged the plausibility of finding both conflicting and complementary forms of fit. Separating the cases when the response variables are endogenous and exogenous is critical because the antecedents are likely to act as contingencies in the performance relationships (Ketokivi and Schroeder, 2004b).

We delimited this study to a macro perspective because this is the most common perspective in both strategic management and organizational science (Molina-Azorín, 2014). Such a perspective is also central to the evaluation of fit within contingency theory (Donaldson, 2001). Because our research is rooted in Operations Management (OM) with a focus on the plant maintenance function, our unit of analysis was the manufacturing plant. Although we ensured that all participants were in agreement with this (Bokrantz et al., 2019) (Appendix A) inevitably some informant responses did cross system boundaries. Our data therefore also reflect a micro perspective; empirical phenomena that exist at the level of individuals. We therefore also provide examples of tentative insights from our data that reflect micro topics suitable to be incorporated in the proposed agenda.

4. Empirical observations and theoretical interpretations

This section presents our empirical observations and corresponding theoretical interpretations. Firstly, we provide a total of three data structures encompassing 20 2nd order categories and seven aggregate dimensions (Section 4.1). Note that our data structures are *not* causal models where the arrows specify the directions of relationships between concepts. Secondly, we transform the data structures into a contingency model and provide plausible theoretical interpretations for the relationships between concepts (Section 4.2). The resultant model is a graphical illustration of our proposed research agenda.

4.1. Data structures

We begin by explaining the categories and aggregate dimensions within the data structure for each focus group question, respectively (Q1, Q2, Q3). The empirical observations are demonstrated first (headings labeled ***Dimension***), where we provide 1st order exemplars in the data structures and example informant quotes in text. Note that while only two exemplary 1st order codes are provided for each 2nd order category, the complete data set consists of over 1500 1st order codes; see Section 3.2 in the first paper (Bokrantz et al., 2019). This is followed by providing relevant data-to-theory connections within each dimension (headings labeled *Theoretical interpretation*). Fig. 3 shows the corresponding data structure focusing on Q1: *When you think of Smart Maintenance – what attributes comes to mind?* Fig. 3 reflects implementation issues with respect to change, investments and interfaces (dimensions 1–3).

Dimension 1: Change context. When discussing organizational change, the informants' arguments often drifted into acknowledging that Smart Maintenance entails a substantial cultural transition, *"It is a new generation of culture. We still reward the firefighting heroes with red capes that fix problems in the middle of the night instead of those who ensure that the problems never occur in the first place. We need to find other to ways to reward that part and take pride in our work."* Although there were elements in the discussions that signified the conceptual domain of such a culture - primarily revolving around trust in technology and data-driven approaches - the informant responses above all reflected a clash between traditional and modern mind-sets. We managed to distil a more specific and distinct category which we believe is culturally rooted and further reflects this clash; the dilemma of algorithm interpretability. The informants uncomfortably expressed their concerns, *"We need to understand these algorithms, they cannot be too complex. If not even managers, engineers or data scientists understand why algorithms want you to make certain decisions, it will be a waste of time and we can stop this whole initiative."* The discussions were intense, characterized by uncertainty and anxiety about the issues of trusting "black box" algorithms. Our analysis intentionally labels this as a dilemma, since dilemmas imply choices, each of which produces undesirable consequences. Based on the participants' discussions, it seemed as if this dilemma is a two-fold matter of transparency. Firstly, algorithms and humans are really no different in this matter. Many Machine Learning (ML) algorithms are black boxes in the sense that the number of interconnected weights can easily outnumber our possibility for explicit understanding. But humans are also black boxes, in the sense that we can readily argue for given inferences, while often struggling in convincingly explaining our sometimes messy, intertwined and idiosyncratic reasoning. Secondly, achieving accuracy without losing transparency is costly. Given enough data, advanced ML algorithms like deep neural nets are often capable of providing highly accurate answers for clearly defined questions, but without comprehensible explanations for how the answer was derived. By contrast, human judgement often relies on relatively few, explainable

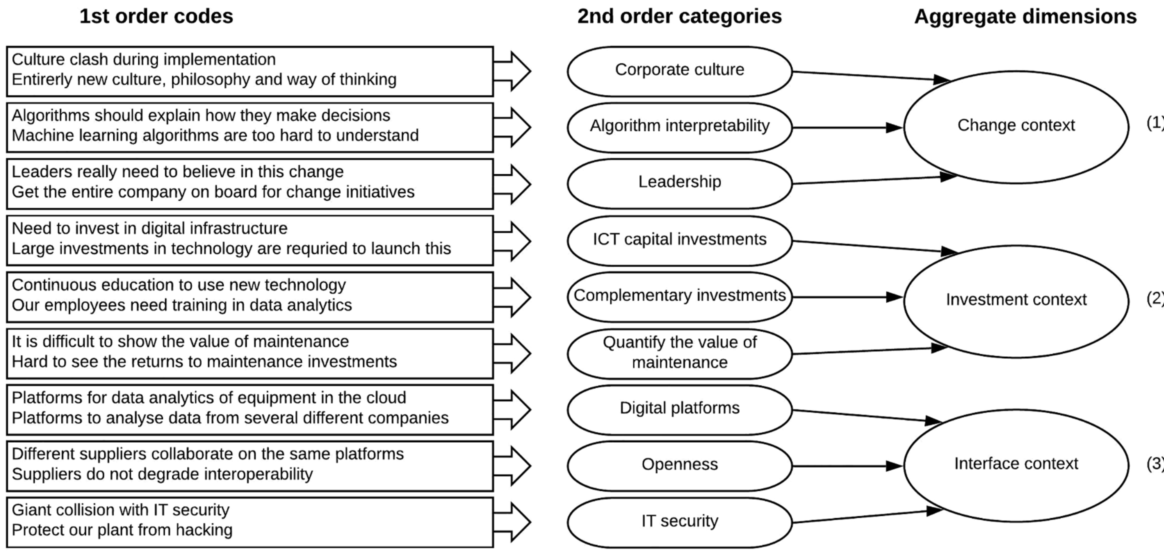

Fig. 3. Data structure from Q1: Change, investment and interface context.

observations for a given case, for which the decision accuracy may be discouragingly low. A fully developed physics-based model of a decision problem is both more accurate and transparent, but the vast resources required to develop and run the model incur large costs, along with a risk that the model might become useless when the context changes. From our understanding of the informant responses, trust in algorithms involves a considerable leap of faith and a clear hesitance about whether accuracy is worth the price. This constitutes a real dilemma for maintenance practitioners that inevitably calls for informed decisions.

To successfully manage this change process, leadership was deemed by participants to be crucial. While the informants did not provide in-depth proposals of desirable leadership traits of maintenance managers, they expressed high expectations for leadership outcomes, *"Leaders will play a very crucial role, they will lead the way to Smart Maintenance and make sure that everyone comes along and has the right prerequisites to do so. Not everyone is going to like this change, it is very hard to get everyone on board."* These expectations existed across all organizational levels. Managers, engineers and technicians collectively expressed that leaders are obliged to spearhead the technological development, understand the performance potential in Smart Maintenance, and ensure that this change does not result in a sense of exclusion amongst employees. The informants almost never mentioned formal decision-making tasks but instead used terms that emphasized the ability of leaders to formulate, communicate, and establish the values, visions, and culture to successfully manage change.

Theoretical interpretation: Change context. Within contingency theory, organizational change is the process of undergoing structural adjustment to regain initial fit (Donaldson, 2001). Two interrelated and particularly useful theoretical lenses to understand the difficulties organizations face during change are adjustment costs and complementaries (Milgrom and Roberts, 1995; Brynjolfsson and Milgrom, 2013). Adjustment costs (also known as menu costs) are costs incurred in response to internal or external contingencies (Englmaier et al., 2018). Organizational change requires money, time and other resources (Brynjolfsson and Milgrom, 2013); these adjustment costs produce organizational inertia and therefore help explain heterogeneity in adoption and ultimately performance (Englmaier et al., 2018). For example, adjustment costs offer part of the explanation for time lags between implementation and performance (Brynjolfsson and Milgrom, 2013). In addition, adjustment costs are likely to be higher when change efforts involve simultaneous change of a set of complementary practices (Milgrom and Roberts, 1995).

For the average maintenance function, adjustment towards the four dimensions that constitute Smart Maintenance is not a case of minor alteration, but requires a substantial change that will incur adjustment costs that prevent rapid adjustment (Miller, 1986; Brynjolfsson and Milgrom, 2013). In particular, our empirics within this dimension consist of factors that tend to be more implicit and less defined. These are important aspects of great importance that require significant managerial attention and effort, and can act as both inhibitors and facilitators to change. The first two categories in this dimension reflect cultural change. We interpreted corporate culture broadly as a source of resistance to change or a catalyst for change, since complementarities have both inertia and momentum (Brynjolfsson and Milgrom, 2013). Adjustment costs often occur as initial "friction" when trying to upset a system of complementarities (Miller, 1986). Yet, once the system begins moving, it will tend to continue in that direction in a virtuous cycle of change (Brynjolfsson and Milgrom, 2013). Algorithm interpretability was interpreted as a specific cultural variable primarily influencing data-driven decision-making. Since trust is central to most economic dimensions, it is natural to assume that achieving trust in algorithms (either by improving interpretability, transparency, or accepting it as an irony of automation) will influence the adoption and performance implications of ML. Within the specific context of industrial maintenance decision-making, adjustment costs may provide theoretical precision to the role of algorithm interpretability within the specific context of industrial maintenance decision-making. Our empirics clearly reflected a cultural resistance to change with respect to decision-making practices. The notion that algorithms may threaten the role of humans in their organization generates adjustment costs in the form of anxiety. This constitutes a form of initial friction that prevents current decision practices from being disrupted. The last category, leadership, was interpreted as a variable that will be decisive for adoption success, simply because any major change will benefit from a clear leadership vision and goals. In summary: transitioning an organization from one equilibrium to another will benefit from a supportive culture and effective leadership.

Dimension 2: Investment context. Our informants voiced their expectations of how implementing Smart Maintenance is likely to be associated with significant investments in both tangible and intangible assets. Our analysis distilled three categories in our data structure (Fig. 3); the investments themselves (in ICT and complementarities) and the challenge in getting approval for maintenance investments due to the difficulty in quantifying their value.

Our informants noted that the current prices for sensors and computing power makes collecting, storing and analyzing data comparably cheap and accessible. Yet, several informants still argued that their plant is in a state that requires significant investments in tangible ICT capital to be successful with Smart Maintenance, *"There will be extreme demands on our technological infrastructure, we probably need to double the infrastructure that we have in production right now."* They also highlighted the need for specific investments in technology to make it easy for anyone to act on insights derived from data. However, taking advantage of these technical capabilities hinges on a wide range of complementary investments in intangible assets. In fact, the informants were careful to point out that technological infrastructure represents only a fraction of the total cost of implementation. Above all, they emphasized the need for education and training of the workforce, *"A lot of education and training is needed to be able to reap the benefits from this, especially regarding making use of data, analyzing data, understanding data, knowing what to do with it."* Informants also stressed the need for investments in re-organization by arguing that even if technology is readily available and the necessary skills have been obtained, the plants might still lack the organizational structure that facilitates its effective use, *"If we are going to succeed in managing all the data and make good decisions, we have to make investments in a different type of organization. This will transform our organization, how we approach problems and whom we collaborate with, a lot of things will happen."* In summary, in order for tangible ICT capital such as sensors and decision support systems to become valuable, these have to be complemented with an array of related investments in intangible assets, such as humans and re-organization.

For investments to occur, they need to be identified, justified, accepted, and executed in projects with accountable costs. From the perspective of the maintenance function, this is easier said than done, and the informants almost spoke hopelessly about the difficulties in getting approval for maintenance investments, *"One critical factor that I see is economic models that* support *this type of behavior. The value of maintenance is invisible in accounting, so it is really hard to motivate investments in these kinds of things."* These informant responses reflect the clash between maintenance investments and accounting policies. Maintenance investments that focus on preventive actions are long-term by definition, with benefits that are only recognizable at a much later stage. The benefits are also difficult to quantify in economic terms since they are almost impossible to isolate and because a substantial portion of the value is realized by avoiding consequences and costs of not performing maintenance. Hence, while the economic value of maintenance investments can be seemingly non-existent or unidentifiable to accountants, it is completely obvious to maintenance employees. Consequently, there are considerable gaps between the value of maintenance investments (as reflected in intermittent calculations of results and balance) compared to its true benefits on various dimensions of plant performance.

Theoretical interpretation: Investment context. The interpretation of this dimension is rooted in the same theoretical lens used within the change context; adjustments to regain fit and its associated costs (Milgrom and Roberts, 1995; Brynjolfsson and Milgrom, 2013). In contrast to the more managerial-oriented aspects of change context, this dimension implies that adoption of Smart Maintenance is associated with adjustment costs in the form of financial investments in both tangible and intangible assets. The key interpretation we make from our empirical data is that while investment in technology is the critical catalyst, the full adoption and consequent performance implications of Smart Maintenance are a function of an array of investments in technology, skills, and organization.

Smart Maintenance is a transition towards new technologies, which is evident in our 2nd order category of ICT capital investment. Although our informants argue that large technological investments are needed, the consistent reduction of the quality-adjusted price of digital technologies has resulted in even the most powerful innovations becoming readily affordable (Brynjolfsson et al., 2002; Yoo et al., 2012). In contrast, our data mirrors the extensive empirical evidence on adjustment costs that highlights the need for two additional perspectives. Firstly, the necessary complementary investments may be much larger than the direct financial cost of the technology itself (Bessen, 2002). Investing in technology is cheap, but enabling its effective use requires large additional investments in the form of new skills, internal re-organization, and revised relationships with external parties (Brynjolfsson and Hitt, 2000). Secondly, performance is a consequence of complementarities between digital technologies, organizational structures and human capital (Bartel et al., 2007). This means that the largest drivers of performance are the intangible assets enabled by technology (not the direct effects of technology per se), each of which are much harder to implement and require more than simply investing in information systems. This difficulty contributes to the time lag between technology investments and observable performance (Milgrom and Roberts, 1995).

Finally, because the theory of complementarities and the empirics of adjustment costs imply that many of the truly valuable assets are intangible, we were not surprised to hear our informants' points concerning the difficulties in quantifying and motivating investments. This does not reflect that maintenance investments have no economic value, but simply that firms adhere to traditional accounting policies (Brynjolfsson et al., 2002). Accountants are typically focused on observable aspects, such as the direct cost of technology (captured in our category of ICT capital) and often neglect the less obvious but equally important complementarities of skills and reorganization, which may not be seen as investments in pure accounting terms (captured in our category of complementary investments). Similarly, the returns on investment are also focused on observables, such as pay-back, while neglecting the less obvious benefits on performance that may take years to materialize. Thus, we argue that since many of the valuable maintenance assets are intangible and notoriously difficult to quantify in accounting terms, maintenance functions face a significant challenge in motivating the entire range of investments in technology, skills, and organization necessary to fully exploit complementarities within Smart Maintenance.

Dimension 3: Interface context. Our informants recognized that value will increasingly be created and traded amongst a large number of external parties. Owing to this, they expressed that there are multiple inherent risks with such relationships. Issues of trust appeared as a central topic. As our pool of participants spanned both manufacturing firms and industrial service providers, i.e. buyers and suppliers, we were able to observe both sides and listen to their respective arguments. It was especially evident that both buyers and suppliers are interested in trading the value that can be created from consolidated equipment data, but that there is a need for mechanisms to manage the inherent risks. From our data, we distilled three distinct categories: digital platforms, openness and IT-security (Fig. 3).

The informants clearly saw the value potential in compounding external resources of data, information and knowledge, and proposed digital platforms to be the primary solution for enabling this in practice. The central aim of such platforms was expressed as consolidating, and thereby maximizing, the amount of useable equipment data for prediction and prescription of maintenance actions. One manager expressed the ideal situation, *"Ideally, you want all machines of the same type to be connected to a common platform so that they can learn from each other. Then you can know that this breakdown is likely to happen soon because it has happened on a lot of other machines"*. As platforms took center stage in the discussions, the informants provided multiple examples of how relationships can be configured with platforms as intermediaries. These included, for example, networks of plants using the same or similar equipment, individual suppliers and all the users of a particular equipment, or multiple suppliers and their corresponding users of equipment with the same or similar features. This would also allow for coordinated collection of context information needed to train ML algorithms with consistent data quality. Evidently, platforms serve as agents for establishing links with external parties. As these configurations were clearly envisioned, many participants readily acknowledged that the accumulated knowledge enabled by platforms will easily outpace the knowledge held by the local plant maintenance function or individual suppliers.

However, opening up their respective inter-organizational boundaries puts both parties at considerable risk in terms of sharing proprietary data and potentially ending up at a knowledge disadvantage. Consequently, both sides argued that they have to engage in protective mechanisms for the purpose of maximizing value and minimizing risks, and we observed that both parties have conflicting perspectives on each other. Buyer organizations (i.e., plant management) perceived that their suppliers' primary protective mechanism is to degrade interoperability and enforce adherence to proprietary technology, *"A factor that hinders this development is that every manufacturer has their own standard and tries to degrade interoperability. Communication interfaces must be open for all of this to work. Openness and transparency is the new standard."* Hence, there were strong opinions amongst buyers that openness is a necessity to create and sustain valuable relationships with their suppliers. When informants from supplier organizations discussed limited interoperability, they echoed that this is contemporary practice but that they were not in principle reluctant to be open, rather the opposite, *"We've already realized this. We communicate extensively with OPCUA and our systems are open already today, none of them are locked. It is obvious that communication interfaces need to be open for this to work at all."* With a specific emphasis on platforms, suppliers expressed the economic motive for openness in terms of attracting a critical mass of customers and enabling the consolidation of distributed innovation in their own platforms. However, they were careful in concurrently noting that the value traded through relationships must obviously be protected to some degree. Instead, the supplier informants flipped the coin and explained their attitude towards the buyer's primary protective mechanisms; strategically restricting the access to equipment data, "*We try to explain to our customers that they own the data and will never lose their intellectual property, but they are still reluctant to share. But I understand this reluctance, the more connected devices that we can monitor, the more knowledge we will have.*" In fact, we did observe this reluctance and lack of trust among buyer informants. Several plant managers expressed a general concern that as service providers and machine vendors become capable of consolidating vast amounts of equipment data, they could exploit this information asymmetry and recommend their most profitable solutions or prescribe unnecessary maintenance actions for the purpose of economic gain. Their explicit protective mechanisms indeed seemed to be restriction of access and requiring that the value of sharing is ensured ex ante, *"Maybe we don't need to open everything, just some parts of it. If we share lots of data, what are we getting back? There must be a profit if we are going to share … That trust issue, it is difficult to see through it."*

However, there was one topic that was almost unanimously perceived as a threat to establishing trust; IT-security. In particular, risks embedded in digital information exchange were perceived as an additional layer of trust compared to traditional business relationships, *"It is obviously a risk that you need to manage to make it work and trust others. Even if you trust a third party you need to know that no one can access sensitive information."* From our interpretation of the informant discussions, IT security threats are reflected in low levels of trust in business relationships based on digital information exchange. Consequently, this acts as a significant barrier to establishing inter-organizational relationships that rely on trading value from large amounts of industrial equipment data.

Theoretical interpretation: Interface context. As our data within this dimension focusses on risks embedded in digital business exchange, we hinged our interpretation on TCE. We interpret these interface context variables as influencing the transactions between two or more parties, such as partnerships and networks of buyers and suppliers. We focus on understanding the complexity of economic exchange from the perspective of plant maintenance rather than on how competition plays out in these settings. Digital platforms play an increasingly important role in a variety of business exchange relationships, such as acting as intermediaries that facilitate transactions in networks (Mcintyre and Srinivasan, 2017). Manufacturing firms are increasingly utilizing platforms to improve maintenance-related service offerings (Cenamor et al., 2017). Our informants primarily emphasized platforms as the solution for applying ML at scale and predict and prescribe maintenance actions based on consolidated cross-plant equipment data. For this to occur in practice, data first need to be shared by multiple users, then assembled and analyzed coherently, and finally redistributed in the form of insights to each user. In this set-up, the platform acts as the intermediary broker with the purpose of maximizing transaction efficiency. Platforms that rely purely on digital exchange dramatically reduce transaction costs along the entire sequence of sharing, reproduction and distribution, thus facilitating transactions to take place that would have otherwise been ignored (Williamson, 1985). The value of platforms comes from direct and indirect network effects (Mcintyre and Srinivasan, 2017). Direct network effects occur when the value to each user depends on the number of other users in the network. In our case - more users lead to more equipment data that leads to better learning and insights for each user. This value may be further augmented by indirect network effects, whereby the value for each user increases when the platform offers a greater variety of complementarities. In our case – suppliers offering additional products and services on the basis of insights derived from consolidated equipment data.

The benefits of platform-mediated networks were obvious to our informants, especially since these allows for accumulating knowledge that easily outpaces what is held by individual parties. Clearly, there is enormous value to be created and traded and, if we are to adhere to TCE prescriptions, the potential for opportunism should always be considered in situations in which a lot is at stake (Williamson, 1975). Hence, we use a TCE lens to interpret our informants' concerns and understand what influences transactions to occur and exchange relationships to survive. Our informants expressed two primary mechanisms under the umbrella of openness: standardization/interoperability and accessibility. With openness, we broadly mean the governing of relationships that sets the conditions for sharing, protection and access to each party's assets. In regards to platform-mediated networks, the general conclusion from theory so far is that there are multiple trade-offs between open and closed platforms and no clear optimum (Mcintyre and Srinivasan, 2017). Our data provides an elaboration of these trade-offs within the specific context of industrial maintenance. Substantial independent investments are needed to enable platform-mediated networks to efficiently create, sustain and trade value from consolidated equipment data. Therefore, it is advantageous for each party to collaborate in order for the entire network to reap the benefits of scale. Such collaborations may include agreeing on standards for interoperability, with the incentive of mitigating transaction costs and hold-up problems that may have previously arisen due to bilateral dependence from mutual investments (Williamson, 1985). This is beneficial for all parties because it allows the platform to attract more users and exploit direct network effects. However, as implied by our supplier informants, too much openness may increase the risk of imitation and require more focus on indirect network effects and profit from complementary products and services, thus incentivizing them to engage in alternative safeguards.

Furthermore, partnerships and networks (platform-mediated or not) are built on the premise that each participant has an interest in sharing and/or protecting their own assets whilst at the same time accessing the assets of others. However, because contracts are always incomplete, exchange relationships are seldom symmetrical (Williamson, 1996), and our informants' concerns reflect how a lack of trust arises due to information asymmetries. These asymmetries may prevent transactions from taking place if the supplier knows a lot more about the transaction than the buyer (e.g., has more and better data to predict maintenance actions) and the buyer sees this information disadvantage as a source of opportunism (e.g. recommending unnecessary actions for profit-maximization) (Williamson, 1985). In such cases, open platforms may reduce information asymmetries and facilitate the transactions to take place. However, the buyers might also try to reduce asymmetries and safeguard against opportunism by strategically restricting access to equipment data. Even if the suppliers do not infringe on IP ownership, the buyer response is reasonable because data is non-rival and its value protected not by ownership but by access. Even if both parties would follow TCE prescriptions and engage in mutual credible commitment to return value that is at least proportional to what is being shared, strategically differentiating the access to data might still be exercised as a safeguard against opportunism at the margin.

Finally, IT security is clearly a source of mistrust for digital exchange relationships. In contrast to formal and informal TCE mechanisms such as contracts and credible commitments (Williamson, 1983), IT security is a technological means for establishing trust. This is important because it seems as if IT security acts as an additional layer of trust on top of what can be accounted for using traditional mechanisms. That is, even if economic actors trust each other to behave honestly (Williamson, 1996), IT security is still a necessary safeguard against opportunism that may be exerted not necessarily by any of the contracting partners but also by actors independent to the relationship. IT security is not the final solution because contracts are still incomplete, but if all actors believe that the digital system serving the exchange is not going to be infringed, transaction costs are reduced. Our key interpretation is therefore simply the importance of this variable. Since digitalization will increase the amount of investments in digital exchange relationships, it is crucial to understand what ex ante safeguards enable such transactions to take place.

The second focus group question centered on consequences. Fig. 4 shows the corresponding data structure from Q2: *What are the consequences of Smart Maintenance?* This structure includes performance dimensions and effects of SBTC. We identified a range of intermediate and final performance variables salient to Smart Maintenance. Furthermore, during our coding procedure, the 2nd order categories covering critical performance dimensions emerged at two macro levels. We interpreted both dimensions concurrently, but the labelling is self-evident; plant performance exists at the level of the plant and firm performance exists at the level of the firm.

Dimension 4 & 5: Plant performance & firm performance. Above all, the responses revolved around plant performance, with a particular focus on implications for production systems. We identified four categories of plant performance at the 2nd order level, each of which consists of multiple individual aspects. Predictably, the bulk of informant responses focused on the internal efficiency of the maintenance function, which we distilled into the category of maintenance performance. The informants clearly indicated the inherent inefficiencies in current maintenance practices, *"This is so typical, you replace things just for the sake of it and because we have done it all these years, without knowing if it is really needed. A lot of time is spent on unnecessary maintenance. So, it is about doing the right maintenance at the right time."* In light of this intent to reduce maintenance-related waste, we observed and grouped the 1st order informant-centric quotes that signified the content of maintenance performance. This included, e.g., maintenance cost effectiveness, conformance quality of maintenance actions, repair lead time, time between failures, inventory precision, and equipment life span. Simply, these responses reflect typical indicators used by industrial firms to measure maintenance performance at the level of the plant.

As a sub-function to production, the informant responses unsurprisingly also covered external effectiveness, or in other words, how maintenance contributes to manufacturing performance. After all, what most plants strive for is to enhance productivity, something the informants were eager to tell us, *"If we know what impacts the condition and status of our equipment, we can run the production process in a better way. What we want is stable production and smooth flows."* Consequently, we grouped all the informant quotes that were indicative of production system output into the category of manufacturing performance. Clearly, this consists of multiple aspects and includes, e.g., manufacturing cost, conformance quality of products as well as throughput; basically, indicators of output for a given set of inputs at the level of the plant.

However, our informants emphasized that it is not just about productivity and also argued for consequences in terms of safety and environmental performance. Maintenance is known as a high-risk occupation, and the informants emphasized the potential to avoid safety hazards, *"All equipment that is taken out of operation is a safety hazard, like fires, gas release, pressure drop, hot media and such. Both that we don't need to stop machines and avoid unnecessary production stops will improve safety."* The pervasive perspective is that preventive actions are safer than reactive actions, owing to factors such as the plannability of tasks and reduced amount of work under the pressure of time. Further, that maintenance activities could contribute to environmental performance was typically argued in terms of extended lifetime of equipment, *"By running the equipment for longer, like that we don't need replace it after six months but instead run it for six more months, we can keep the production running in a better way and improve sustainability, especially energy consumption."* Although discussions regarding other environmental indicators, such as energy consumption and emissions, had an undertone of economic rationality, the informant responses were primarily motivated by a desire to contribute to the realization of societal goals for sustainability.

We identified two final performance dimensions at the level of the firm: financial performance and competitive advantage (final in the sense that they constitute end goals of economic activities in competitive

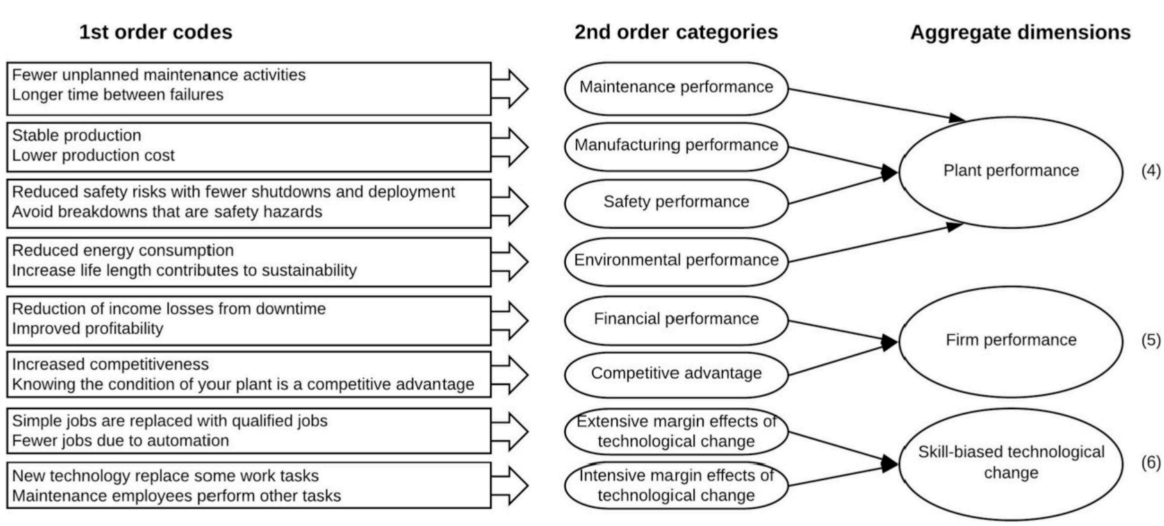

Fig. 4. Data structure from Q2: Consequences of Smart Maintenance.

markets). Although OM scholarship often uses the former as a proxy for the latter, they are distinct. Firms may be profitable but not competitive and vice versa, and while many firms can be profitable only few can have a competitive advantage (Ketokivi, 2016). Economic dimensions of firm performance were frequently mentioned and discussed by the informants. We constructed the 2nd order category of financial performance by distilling responses regarding indicators such as ROA and ROI together with arguments for maintenance-profitability links. One informant explained such links at their plant as, *"Our profit is often linked to the dependability of the plant. Downtime is extremely costly for us, so if maintenance improves dependability then it will lead to profits."* When probed to elaborate their reasoning, the informants did not clearly distinguish between plant- or firm-level financial performance and loosely acknowledged that some determinants of financial performance are normally uncontrolled by the individual plant, such as sales volumes. However, most commonly the informant responses boiled down to the notion that if maintenance practices contribute to improving manufacturing performance, reflected in some measure such as producing with shorter throughput times or absorbing volume increases at unaltered unit cost, this increase in productivity is plausibly linked to profitability at the level of the firm.

The informants also frequently argued that the use of Smart Maintenance could be a source of competitive advantage. Similar to the discussions of financials, probing for elaborations resulted in that the more reflective participants reasoned that although facets of plant performance are important determinants, competitive advantage at the level of the firm is also influenced by a myriad of variables not directly related to operations. One informant summarized these reflections by stating, *"Sure, if you increase internal efficiency then competitiveness should increase also. But competitiveness is tricky, it is dependent on so much more than just the industrial system that produces the products."* The informant discussions hovered over the topic that depending on the characteristics of the market in which the firm operates, there is considerable variation in the extent to which the features of the production system versus the features of the products act as the main determinants of competitive advantage. As observant researchers, we read the situation as if the informants reasoned that using certain maintenance practices may be an important complement for competitive advantage in certain business environments.

Theoretical interpretation: Plant & firm performance. A central goal shared by OM, strategy, organization science and economics is to discover the drivers of performance. However, despite the importance of performance across fields, performance has been subject to much critique and discussion regarding both conceptualization and measurement (Ketokivi and Schroeder, 2004a). One particular problem is inconsistency; treating performance as a general concept in theory but as a set of specific concepts in empirical work (Miller et al., 2013). To achieve consistency, the approach taken in theory building should be carried out through theory testing. The favorable approach is not to treat performance as a general concept but as a domain of loosely related but distinct, separate concepts. However, this choice involves difficult trade-offs: it increases accuracy because predictions and explanations might be more grounded and meaningful, however it reduces simplicity because arguments need to be developed for each specific performance variable (Miller et al., 2013). These trade-offs challenged us because theoretical interpretations should ideally capture the complexity of relationships at all levels, yet do so parsimoniously. In this study, we focused on finding the appropriate dimensions of performance that are suitable for linking adoption heterogeneity to performance heterogeneity. They serve the purpose of guiding maintenance scholars in more detailed, confirmatory empirical work.

Thus, our interpretation of plant and firm performance is based on the following rationale: A meaningful single latent variable for plant or firm performance does not exist. Instead, the 2nd order categories are considered as a set of distinct concepts that are loosely related within each level. For example, maintenance, manufacturing, safety and environmental performance are four distinct but related concepts at the level of the plant. This level is sufficient for hypothesizing that the effects of Smart Maintenance may be positive or negative for several, separate dimensions of performance. Each performance dimension could be operationalized using perceptual or quasi-perceptual measures and meaningfully examined using valid latent constructs (Ketokivi and Schroeder, 2004a). However, within each 2nd order category we distilled 1st order informant quotes that each may be considered a specific variable of performance (production cost, conformance quality, ROI etc.). If hypotheses about detailed mechanisms ought to be completely tractable, each category should ideally be disaggregated and empirically examined with this degree of precision. For example, the effect of data-driven decision-making may be hypothesized to be positive in multiple dimensions of maintenance performance, but the mechanism may not necessarily be the same with respect to both cost and repair lead time. In summary, managing these trade-offs and achieving consistency across theory building and theory testing is far from easy, but it deserved attention by empirical maintenance researchers because it allows us to offer more rigorous and important insights that are valuable to both industry and academia (Miller et al., 2013).

Dimension 6: Skill-biased technological change. In contrast to measurable performance, our informants exemplified consequences of Smart Maintenance that reflected automation anxiety and concerns for how advancements in technology will reshape tasks and jobs. We distilled this into two 2nd order categories of skill-biased technological change (Fig. 4). Firstly, the informants were concerned about employment polarization along the extensive margin. That is, reallocation of workers across occupations. Several responses reflected a general perception of reduced demand for labor, with specific arguments proposing that jobs will be lost within occupations characterized by extensive on-job experience, *"We are going to lose many of the maintenance artisans, the ones with experience, for them this is really scary."* These responses primarily reflect concerns for substitution effects of automation - where technology replaces tasks previously performed humans – with potential consequences being falling aggregate labor demand or shifts in demand from low-skill to high-skill occupations. Secondly, and in contrast, responses focused more positively on effects along the intensive margin. That is, changes to the task content within occupations. Instead of worrying about technological unemployment, informants calmed the debate and noted that a much more profound effect will come in the form of new tasks, *"Jobs don't disappear, they just change. That is always the case with automation, some tasks become superfluous but they are just replaced with other tasks."* The participants then converged into intensive discussions on how these effects will be reflected in novel tasks for maintenance employees, new roles and occupations within the maintenance function, development of new skills, and redistribution of working hours from shop floor to back office. Taken together, these extensive and intensive margin effects of technological change were met with both anxiety and optimism by our informants.

Theoretical interpretation: Skill-biased technological change. Anxiety about technological change in general, and automation in particular, have been persistent throughout history, especially in the form of concerns about its impact on labor, wages, employment and inequality (Acemoglu and Restrepo, 2018a). SBTC provides the theoretical explanations for these phenomena and thus enabled us to interpret the data within this dimension. At the core of SBTC lies the conjecture that technological progress and skills have always been relative complements (Goldin and Katz, 1998). SBTC arises from shifts between technologies, often spurred through reductions in input prices, and this leads to substitution and complementary effects on labor. Typically, technology substitutes labor for routine tasks and complements labor for non-routine tasks. Together, these effects raise the relative demand for workers who hold a comparative advantage in non-routine tasks, thus explaining the shifts in labor demand and returns to certain types of skills (Autor, 2015). This relative demand is the *skill-bias*; that the returns to skills is determined by a race between the supply of skills and technological change. Within this view, new technologies typically increase the relative demand for more educated, skilled and advantageous workers (Acemoglu and Autor, 2011). In our data, we clearly observed indicators of substitution (extensive margin) and complementary (intensive margin) effects. These observations allow us to infer the contingency creating the effects. Since we interpret Smart Maintenance as reflective of an ongoing technological change that is indeed skill-biased, an important environmental contingency is not just a general aspect of the business or task environment such as technological change (Sousa and Voss, 2008), but more precisely *shifts between technologies* (Goldin and Katz, 1998).

However, past theory and evidence of SBTC may be not enough to explain how technology and skills might interact in the future (Autor, 2014). This concern is spawned from observing a technological shift at the intersection between advancements of AI and reduction in input prices for computational power (Acemoglu and Restrepo, 2018a). In the past, highly skilled workers were protected from substitution because they specialized in complex tasks requiring complementary skills, such as human judgement. However, many of tasks are now also candidates for cognitive automation using AI (Acemoglu and Restrepo, 2018b). This opens up for an array of new forces that both fuel and countervail the substitution and complementary effects (Acemoglu and Restrepo, 2018a, 2018b). Dissecting our data with this lens allows us to make an important interpretation that reinforces the findings of the preceding paper (Bokrantz et al., 2019). Our data implies that intensive margin effects will create new tasks for maintenance workers and thus compensate for some of the negative extensive margin effects. These effects are skill-biased and therefore explain the increase in demand for both generic and specific KSAOs that make up the human capital resource (Bokrantz et al., 2019). That is, the maintenance function responds to this *skill-based* environmental change by purposefully adjusting its human capital resource. However, the human capital resource dimension spawned from observing a mismatch between technology and skills, which leads us to arguably the most important catch: the skills that are becoming increasingly valuable are not readily available on the labor market. If the shifts in demand cannot be absorbed by supply response, this skills gap may result in extensive implementation lags and unrealized performance gains from Smart Maintenance.

After focusing on the consequences of Smart Maintenance, the last part of the focus group asked Q3: *What does absence of Smart Maintenance mean?* When the informants focused on visualizing for themselves what a situation of absence of Smart Maintenance would look like, institutional arguments for adoption appeared. We constructed three categories within the aggregate dimension of institutional isomorphism (Fig. 5).

Dimension 7: Institutional isomorphism. Firstly, absence of Smart Maintenance was associated with preserving the status quo - the conservation of the current state of affairs, *"Everything stays at it is today and we get stuck in a rut. We do as we have always done, nothing changes. We remain stagnant with the same old mind-set."* Most informants agreed that the status quo was not worth protecting and clearly expressed a negative attitude towards organizational stagnation. Consequently, they committedly expressed their forward-looking intentions to take actions to challenge the status quo, *"We need to motivate this to the top management now. We must develop, we cannot settle."* As the motive to such actions, the informants highlighted several driving forces using both sociological and economic arguments. We were not capable of clearly separating the two types of arguments, as they were intertwined in the informant responses, but we distilled them into two 2nd order categories in our data structure: coercive and mimicry pressures.

The existence of coercion was sharply framed by the respondents, *"We are forced to do this. Sooner or later we have to, it is simply not possible to opt out."* Sociological arguments particularly revolved around pressures to follow societal developments. The manufacturing industry might no longer be an innovator or early adopter of the latest technology, but the informants strongly inferred that they have to keep up with the rest of society, especially as a way to demonstrate the firm's modernity and environmental awareness. However, these pressures were predominantly economically motivated and salient to buyer-supplier relationships. Several informants expressed how suppliers would potentially lose interest for plants with outdated maintenance practices, or try to enforce change by only accepting modern plants as customers, restricting their offers to the latest technology or delimiting backwards compatibility with existing solutions.

Pressures to mimic other plants were also prevalent among the informants. Mimicking arguments typically expressed uncertainty and anxiety about the response to industrial trends and trade-offs between first and late mover advantages, *"It is a big difference between leading and following, so we have to make wise decisions in the beginning. Maybe we don't need to go all in right away but it is probably good to join the trend."* Similarly, it was also a matter of following the critical mass of adopters, *"Even if one company does not work with what everyone else does, other branches and other companies in the same branch will still do it because everything is moving in that direction and everyone agrees do to it."* Our informants also justified mimicry as attempts to enhance performance in terms of profits and competitiveness. With clear intentions for profit-maximization, one informant stated, *"We have to be on our toes the whole time, otherwise it easy to fall behind and loose production to plants that work with Smart Maintenance. We obviously have pressures that we need to act on to stay profitable."* With competitiveness in mind, one informant argued, *"The plants who don't do this will fall behind, a competitive disadvantage."*

Hence, there seem to be several institutional forces at play with respect to the adoption of Smart Maintenance. The informant responses also uncovered the consequences of absence of Smart Maintenance; that it will be expensive and difficult to catch up. In other words, the consequences of non-conformity to these institutional pressures are associated with both considerable cost and effort. It therefore appears as if plants are substantially motivated to adopt Smart Maintenance regardless of whether it makes sense strategically or if it has been demonstrated to improve performance.

Theoretical interpretation: Institutional isomorphism. Since our informants expressed both sociological and economic arguments for isomorphism that were difficult to separate, we interpreted our data using both variants of institutional theory that are relevant to OM: the sociological variant (Dimaggio and Powell, 1983) and the economic variant (Haunschild and Miner, 1997). The sociological variant assumes that actions are motived by attempts to achieve legitimacy, where three mechanisms drive isomorphism: coercive, mimetic, and normative.

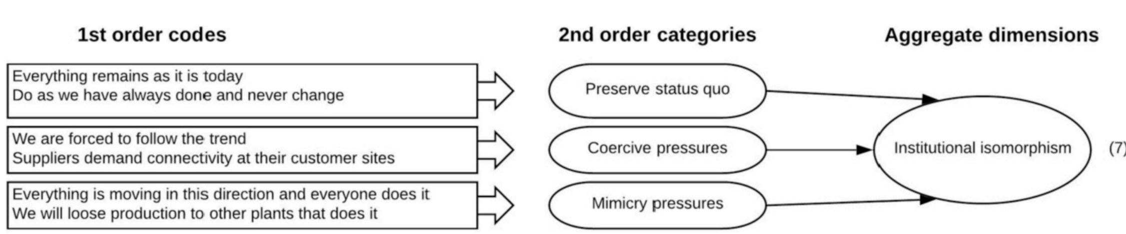

Fig. 5. Data structure from Q3: Institutional isomorphism.

Coercive isomorphism occurs due to formal and informal pressures exerted by other organizations or expectations from society; mimetic isomorphism occurs when organizations model themselves after those that are perceived successful; and normative isomorphism occurs due to professionalization (Dimaggio and Powell, 1983). Within OM, the normative is typically collapsed within the coercive (Ketokivi and Schroeder, 2004b). In contrast, the economic variant assumes that actions are economically motivated (seeking efficiency) and that organizations come to resemble one another through three modes of mimicry: frequency-based, trait-based and outcome-based imitation. These three refer to mimicking actions previously taken by many organizations; mimicking organizations with selected traits such as size; or mimicking actions appearing to have resulted in success for other organizations, respectively (Haunschild and Miner, 1997). All mechanisms may operate simultaneously within a group of organizations, and collectively, they lead to that certain organizational practices become perceived as legitimate or valuable and consequently adopted even in the absence of evidence for their effectiveness (Dimaggio and Powell, 1983; Ketokivi and Schroeder, 2004b). Our data clearly suggests that both perspectives have merit in the context of plant maintenance, i.e., that the motives for conformance to institutional pressures may be gaining legitimacy and/or efficiency. This also holds for the opposite pole of non-conformance, where the sociological variant perceives that absence of adoption could signal illegitimacy (Volberda et al., 2012), while our data primarily suggests inefficiency. After all, there exists exactly zero empirical evidence of performance links with respect to this conceptualization of Smart Maintenance, which is fully consistent with the institutional argument (Ketokivi and Schroeder, 2004b).

Examples of micro topics: Owing to our deliberate macro perspective, we end our disclosure of empirical observations and theoretical interpretations by providing examples from our data that reflect important micro topics. Although they are not core findings, the intention is to encourage both macro and micro research within our proposed research agenda. From Q2, we observed the possibility for two individual-level consequences: *job satisfaction* and *organizational attractiveness*. In line with adjustment costs and complementarities (Milgrom and Roberts, 1995; Brynjolfsson and Milgrom, 2013), it is plausible that when maintenance functions undergo structural adjustment along multiple dimensions of a socio-technical system, maintenance employees will experience drastic changes in their daily work. These changes are likely to affect their perceptions of personal and work outcomes (Bala, 2013). Our informants' responses reflected this, and it is therefore theoretically plausible that adoption of Smart Maintenance will lead to changes in job characteristics and organizational attributes that may in turn influence perceived job satisfaction and attractiveness to prospective employees. Our data from Q3 further suggests that substantial individual and collective effort is required to disrupt the status quo and achieve fit with new institutional environments, irrespective of whether this is motivated by the legitimacy and efficiency of conformance or by the consequences of non-conformity. Therefore, in order to understand the actual, lived experiences of human actors and the multiple forms of agency that are embedded within the process of institutional change, we propose the study of *institutional work*; the practices of individual and collective actors aimed at creating, maintaining and disrupting institutions (Lawrence et al., 2011).

4.2. Contingency model

The empirical observations and theoretical interpretations captured in our data structures in Section 4.1, together with the concept clarity achieved in the preceding paper (Bokrantz et al., 2019), presents the in-depth elaboration of the concept of Smart Maintenance. However, these are static descriptions of dynamic phenomena that do not formally specify the relationships between concepts. Therefore, we now transform the contingencies, responses and performance implications into a complete contingency model. We do so by taking our schematic model (Fig. 3), fill the boxes with content, and explain the relationships represented by the arrows. Ideally, a full contingency model should account for all relationships and be completely tractable. However, this again involves a trade-off between simplicity and accuracy. Focusing on accuracy, this would be done solely by means of selection and interaction (Cases 1 and 4 in Fig. 3). More precisely, it would involve taking one individual contextual variable at a time and relating it to one response variable, then relating their interaction to one performance variable. Because of our voluminous qualitative data, this would require us to formulate an array of bivariate or constrained multivariate relationships, which would be long-winded, inelegant and possibly inaccurate because of complex interrelationships between the many contingencies. Focusing instead on simplicity, the model would be specified using the system approach (Cases 2 and 5 in Fig. 3) whereby each bundle of contingencies is matched to a bundle of responses, and then to performance. This allows for a more parsimonious and holistic model. However, it would not be completely tractable with respect to all underlying mechanisms. Since our aim with this study is to propose a research agenda based on important conceptual variables and an overall pattern of relationships, we emphasize the system approach. Naturally, we encourage future studies that embrace our agenda to also specify and test completely tractable hypotheses at the lowest disaggregated level. The model is presented in Fig. 6.

The contingency model in Fig. 6 represents a graphical illustration of our proposed research agenda. The model consists of a set of variables aimed at explaining heterogeneity in adoption of Smart Maintenance and linking this to performance heterogeneity. These links are ideally studied from both a sufficiency and necessity perspective. In other words, answering what ensures performance to exist (sufficiency) as well as what prevents performance to exist (necessity) (Dul et al., 2010). Empirical evidence under this agenda offers plausible explanations for the two basic empirical research questions with respect to heterogeneity: (1) *Why is this?* and (2) *What are the implications?*

On the left side of our model, treating Smart Maintenance as endogenous and including internal fit, there are six important origins of heterogeneity in adoption of Smart Maintenance: institutional isomorphism, environmental contingencies, complementarities, change context, investment context, and interface context. Together, they offer two types of explanations: (1) *why* maintenance functions undergo structural adjustment, and (2) why adjustment is *difficult*. With respect to the first type, institutional isomorphism (the sociological variant) suggests that managers adapt their practices to achieve legitimacy (Dimaggio and Powell, 1983), implying that Smart Maintenance diffuses through coercion and mimicry. Environmental contingencies suggest that managers carefully analyze the external environment, take into consideration the internal characteristics of the firm, and adapt their practices accordingly (Donaldson, 2001). Complementarities suggests that managers seek to exploit internal synergies by consciously adopting a tight cluster of mutually supportive elements (Milgrom and Roberts, 1995), implying that maintenance managers intentionally adopts the four dimensions of Smart Maintenance simultaneously. Contingency fit and institutional fit are both central to external fit (Volberda et al., 2012; Van De Ven et al., 2013), and both external and internal fit is important (Miller, 1992). With respect to the second type, contextual factors reflect implementation issues. The change context and investment context suggest that plants in which the maintenance function experiences high adjustment costs, as reflected in part by cultural resistance, lack of trust, absence of leadership and/or investment constraints, is likely to find it more difficult to adopt Smart Maintenance (Brynjolfsson and Milgrom, 2013; Englmaier et al., 2018). Further, because formal and informal contracts that govern the relationship between external parties are both difficult to establish and change, in part because they are always incomplete (Williamson, 1996), it follows that digital platforms, openness and IT-security may influence the establishment of relational links to external parties.

On the right side of our model, treating Smart Maintenance as

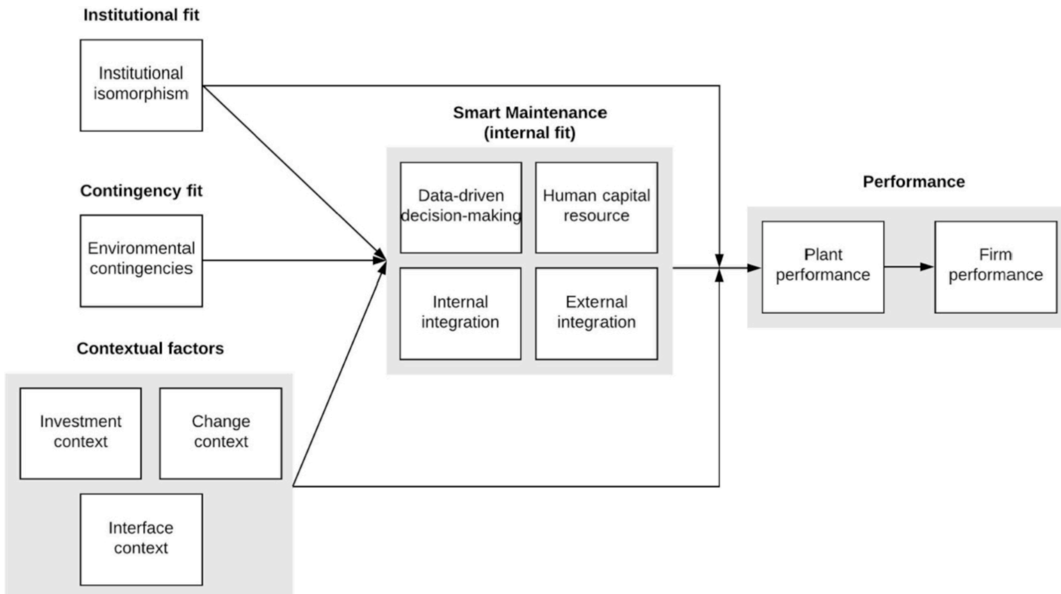

Fig. 6. Contingency model of Smart Maintenance.

exogenous, there are two dimensions that represent the link between heterogeneity in adoption and heterogeneity in performance at the plant- and firm-level. They offer plausible explanations for how Smart Maintenance influence performance; empirical evidence that essentially every maintenance manager desires to know. Here, fit dictates performance: achieved internal or external fit is rewarded with performance improvement, whilst misfit produces a performance penalty. In other words, maintenance functions that achieve fit perform better than those who don't. Individual-level outcomes are also important micro topics, but they are not used to evaluate macro fit. We have identified three distinct forms of fit: contingency fit, institutional fit and internal fit. Because Smart Maintenance is not the only available configuration, both internal fit and external fit are important (Miller, 1992). Contingency fit holds that performance is a consequence of fit between structure and contingencies (Donaldson, 2001). Institutional fit represents the conformance to institutional pressures, which may increase performance through reinforcing mechanisms such as collective learning (Dimaggio and Powell, 1983). Internal fit represents the achievement of complementarity between the elements of a system (Milgrom and Roberts, 1995; Brynjolfsson and Milgrom, 2013), where performance comes from the entire system of multiple interactions among the four dimensions of Smart Maintenance.

However, focusing on direct effects of Smart Maintenance on some aggregate measure of performance leaves out an array of mediators and moderators at different levels. Therefore, there exists four performance dimensions at the level of the plant and two performance dimensions at the level of the firm. Although it is plausible that certain OM practices that lead to plant performance also contribute to firm performance, it is critical to distinguish that firm-level effects do not necessarily derive directly from operations (Bromiley and Rau, 2016). Adjustment costs also help to link adoption with performance (Englmaier et al., 2018), especially in the form of explanations for the time lags between adoption and performance (Brynjolfsson and Milgrom, 2013). More precisely, adjustment costs suggest that if all maintenance functions in a similar industrial setting were subject to the same exogenous industry shock, the outcome would differ. Even if all maintenance managers in all plants were fully aware of the best way to align its organization to a certain environmental contingency; were coerced by the same policy dictating the adoption of a certain technology; or fully understood the nature of complementaries between a certain set of publicly available practices; the outcome would differ because their starting points differ. Adjustment costs (broadly defined), determine the difficulty and thereby the speed with which practices can be adopted. They thereby also ultimately determine performance outcomes following the same shock (Englmaier et al., 2018). However, it is important to remember that most explanations for slow adjustments and imperfect fit are still endogenous to managerial choice (Ketokivi and Mcintosh, 2017).

5. Discussion and conclusions

The objective of this paper was to provide an empirically grounded research agenda that will guide scholars and practitioners with respect to Smart Maintenance. We approached this by means of an inductive, empirical research approach in close collaboration with more than 110 participants from over 20 different firms. Specifically, by adopting an orientation towards theoretical prescience (Corley and Gioia, 2011) and employing a multitude of general theories, we have inductively identified an array of conceptual variables that can be empirically measured. This includes the four dimensions of the concept of Smart Maintenance; environmental contingencies and institutional isomorphism; implementation issues related to change, investments and interfaces; as well as the most important performance dimensions at the plant and firm level. We transform all of this into a complete contingency model that specifies the overall pattern for how the variables are related to one another. These findings form an empirical research agenda for understanding of how Smart Maintenance impacts the performance of manufacturing plants; a pressing problem for both scholars and practitioners.

5.1. Managerial and scientific contributions

For managers, the agenda highlights the importance of having a holistic perspective on Smart Maintenance. The full contingency model, together with the elaborated concepts and their relationships, guides industrial maintenance managers in identifying key drivers of both adoption and performance. An increased understanding of these drivers can serve as input for developing policies and strategies for successful implementation of Smart Maintenance. In other words, the results from this study can used as a blueprint for maintenance managers when designing and implementing holistic maintenance strategies that cover both technological, human and organizational aspects. An holistic maintenance strategy for Smart Maintenance would focus on a careful, coordinated and joint implementation effort of all four dimensions of Smart Maintenance. In addition, implementation success could be ensured by continuously reflecting on constraints in terms of investments, change and interfaces, as well as other potentially missing complementarities.

For scholars, the agenda intends to advance the scientific knowledge of industrial maintenance management by inspiring to more empirical research (Fraser et al., 2015). Our findings successfully complement the already vast scientific knowledge within the field. This complementarity stems from our use of a drastically different approach to theorizing. Specifically, we have elaborated on general theories from economics, organizational science, strategic management and sociology, thereby introducing novel theoretical perspectives to the field. In short, where others see technology, we see organization. Further, we believe that establishing a unified agenda for maintenance research may inspire to scholar-to-scholar communication that is centered around a common goal: informing policy and practice through empirical research. To this end, the contingency model specifies *what the field needs to know* (Corley and Gioia, 2011). Owing to our phenomenon-driven research impetus and close collaboration with practitioners, the initial relevance of our agenda is ensured (Corley and Gioia, 2011; Fraser et al., 2015). Societal influence is likely to follow if the agenda is pursued rigorously.

5.2. Pursuing the proposed research agenda

We consider Smart Maintenance to be a promising concept for which scholarly work is needed to elevate its use and/or remove barriers to adoption (Sousa and Voss, 2008). No theories are tested in this study, and we therefore see two main avenues for future scholarly work within the agenda. Firstly, there is room for further exploratory work and theoretical refinement regarding both the concepts themselves, as well as the mechanisms underlying the relationships between concepts. Thereafter, it would be very fruitful if the field gradually moved from exploratory work to confirmatory work, studying the validity of the concepts as well as the magnitude and direction of their relationships. The boxes and arrows in Fig. 6 are all testable empirical propositions, and the agenda thereby forms a clear path to theory testing that would greatly advance the knowledge within the research community.

With respect to pluralism in theoretical perspectives, our proposed agenda is not limited to the theoretical lenses used in this study. For example, we viewed organizational adjustment using an economic lens with a focus on heterogeneity (i.e. adjustment costs), and further research could complement this view by incorporating more perspectives from change management literature. Although we approached this study from a macro perspective, our agenda also encourages studying micro topics, which we exemplify with our empirics. We are confident that all theoretical perspectives can be incorporated within the agenda. With respect to pluralism in methodological approaches, both conceptual refinement using qualitative case studies as well as theory testing using quantitative surveys and psychometric measurement are effective means. Specifically, our contingency model supports the development and validation of measurement instruments that are likely to capture a substantial part of the cross-plant heterogeneity in adoption and performance with regards to contemporary and future maintenance practices within the manufacturing industry. In fact, we do not have to limit ourselves to conventional empirical workhorses like cross-sectional surveys using a constrained set of variables measured in a certain way. Maintenance scholars are skilled in data science topics like ML (Lee et al., 2014; Roy et al., 2016; Ruschel et al., 2017). Therefore, we propose pooling the knowledge of sophisticated data analytical techniques with that of empirical measurement properties such as construct validity; combining our inferences from significance testing with incremental validation of multiple models; and creating a unified modeling and algorithmic culture (Tonidandel et al., 2018). This future work could constitute a truly exciting development capable of producing scientific knowledge in the form of valid prescriptions such as: *if a plant does X, performance will improve!*

5.3. Final conclusions

Our research agenda aims to uncover the origins of differences with respect to *how*, and *how well*, maintenance functions within manufacturing plants do things. In other words, explaining heterogeneity in adoption and performance with respect to Smart Maintenance. The contingency model covers a variety of origins by incorporating both external fit (in the form of alignment of the maintenance function for environmental and institutional fit), as well as internal fit (through the configuration of the four underlying dimensions of Smart Maintenance). The model also addresses implementation issues in the form of adjustment costs, thereby providing clear guidance for industrial managers when designing long-term strategies to successfully adopt Smart Maintenance. We hope that this research will inspire maintenance scholars to pursue this common agenda, thereby contributing to our vision of advancing the maturity of empirical maintenance research that informs policy and practice. We are convinced that this will improve the field of industrial maintenance management research with respect to its societal role of enabling more economically, socially and environmentally sustainable production systems.

Declaration of competing interest

None.

Acknowledgements

We direct our gratitude towards all the individuals who contributed to this research, especially all the working professionals who devoted their time and interest to this study. The focus group participants and interviewees were not only sources of empirical data but also played a key role in the theoretical interpretations and specification of the contingency model.

This work was supported by VINNOVA, Swedish Agency for Innovation Systems [grant number 2017-01652]. This work has been performed within the Sustainable Production Initiative and the Production Area of Advance at Chalmers. The support is greatly appreciated.

References

Aboelmaged, M.G., 2014. Predicting E-readiness at firm-level: an analysis of technological, organizational and environmental (toe) effects on E-maintenance readiness in manufacturing firms. Int. J. Inf. Manag. 34, 639–651.

Acemoglu, D., Autor, D., 2011. Skills, tasks and technologies: implications for employment and earnings. In: Handbook of Labor Economics. Elsevier, pp. 1043–1171.

Acemoglu, D., Restrepo, P., 2018. Artificial Intelligence, Automation and Work. National Bureau of Economic Research.

Acemoglu, D., Restrepo, P., 2018. Low-skill and high-skill automation. J. Hum. Cap. 12, 204–232.

Antonakis, J., 2017. On doing better science: from thrill of discovery to policy implications. Leadersh. Q. 28, 5–21.

Antonakis, J., Bendahan, S., Jacquart, P., Lalive, R., 2010. On making causal claims: a review and recommendations. Leadersh. Q. 21, 1086–1120.

Autor, D., 2014. Polanyi's Paradox and the Shape of Employment Growth. National Bureau of Economic Research Cambridge, MA.

Autor, D., 2015. Why are there still so many jobs? The history and future of workplace automation. J. Econ. Perspect. 29, 3–30.

Bala, H., 2013. The effects of it-enabled supply chain process change on job and process outcomes: a longitudinal investigation. J. Oper. Manag. 31, 450–473.

Bartel, A., Ichniowski, C., Shaw, K., 2007. How does information technology affect productivity? Plant-level comparisons of product innovation, process improvement, and worker skills. Q. J. Econ. 122, 1721–1758.

Bessen, J., 2002. Technology adoption costs and productivity growth: the transition to information technology. Rev. Econ. Dyn. 5, 443–469.

Bokrantz, J., Skoogh, A., Berlin, C., Stahre, J., 2017. Maintenance in digitalised manufacturing: delphi-based scenarios for 2030. Int. J. Prod. Econ. 191, 154–169.

Bokrantz, J., Skoogh, A., Berlin, C., Wuest, T., Stahre, J., 2019. Smart maintenance: an empirically grounded conceptualization. Int. J. Prod. Econ.

Bromiley, P., Rau, D., 2016. Operations management and the resource based view: another view. J. Oper. Manag. 41, 95–106.

Brynjolfsson, E., Hitt, L.M., 2000. Beyond computation: information technology, organizational transformation and business performance. J. Econ. Perspect. 14, 23–48.
Brynjolfsson, E., Hitt, L.M., Yang, S., 2002. Intangible assets: computers and organizational capital. Brook. Pap. Econ. Act. 2002, 137–181.
Brynjolfsson, E., Milgrom, P., 2013. Complementarity in organizations. Handb. Organ. Econ. 11–55.
Campbell, J.L., Quincy, C., Osserman, J., Pedersen, O.K., 2013. Coding in-depth semistructured interviews: problems of unitization and intercoder reliability and agreement. Sociol. Methods Res. 42, 294–320.
Cenamor, J., Sjödin, D.R., Parida, V., 2017. Adopting a platform approach in servitization: leveraging the value of digitalization. Int. J. Prod. Econ. 192, 54–65.
Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I., Jussila, A., 2018. The perceived value of additively manufactured digital spare parts in industry: an empirical investigation. Int. J. Prod. Econ. 205, 87–97.
Corley, K.G., Gioia, D.A., 2004. Identity ambiguity and change in the wake of a corporate spin-off. Adm. Sci. Q. 49, 173–208.
Corley, K.G., Gioia, D.A., 2011. Building theory about theory building: what constitutes a theoretical contribution? Acad. Manag. Rev. 36, 12–32.
Creswell, J.W., Miller, D.L., 2000. Determining validity in qualitative inquiry. Theory Pract. 39, 124–130.
Dalenogare, L.S., Benitez, G.B., Ayala, N.F., Frank, A.G., 2018. The expected contribution of industry 4.0 technologies for industrial performance. Int. J. Prod. Econ. 204, 383–394.
Dimaggio, P., Powell, W., 1983. The iron cage revisited: institutionalized isomorphism and collective rationality in organizational fields. Am. Sociol. Rev. 48, 147–160.
Donaldson, L., 2001. The Contingency Theory of Organizations. Sage.
Dul, J., Hak, T., Goertz, G., Voss, C., 2010. Necessary condition hypotheses in operations management. Int. J. Oper. Prod. Manag. 30, 1170–1190.
Englmaier, F., Foss, N.J., Knudsen, T., Kretschmer, T., 2018. Organization Design and Firm Heterogeneity: towards an Integrated Research Agenda for Strategy.
Flynn, B.B., Sakakibara, S., Schroeder, R.G., Bates, K.A., Flynn, E.J., 1990. Empirical research methods in operations management. J. Oper. Manag. 9, 250–284.
Frank, A.G., Dalenogare, L.S., Ayala, N.F., 2019. Industry 4.0 technologies: implementation patterns in manufacturing companies. Int. J. Prod. Econ. 210, 15–26.
Fraser, K., Hvolby, H.-H., Tseng, T.-L., 2015. Maintenance management models: a study of the published literature to identify empirical evidence: a greater practical focus is needed. Int. J. Qual. Reliab. Manag. 32, 635–664.
Gioia, D.A., Corley, K.G., Hamilton, A.L., 2013. Seeking qualitative rigor in inductive research: notes on the Gioia methodology. Organ. Res. Methods 16, 15–31.
Goldin, C., Katz, L.F., 1998. The origins of technology-skill complementarity. Q. J. Econ. 113, 693–732.
Haunschild, P.R., Miner, A.S., 1997. Modes of interorganizational imitation: the effects of outcome salience and uncertainty. Adm. Sci. Q. 472–500.
Holmström, J., Ketokivi, M., Hameri, A.P., 2009. Bridging practice and theory: a design science approach. Decis. Sci. J. 40, 65–87.
Jonsson, P., 2000. Towards an holistic understanding of disruptions in operations management. J. Oper. Manag. 18, 701–718.
Ketokivi, M., 2016. Point–counterpoint: resource heterogeneity, performance, and competitive advantage. J. Oper. Manag. 41, 75–76.
Ketokivi, M., Mcintosh, C.N., 2017. Addressing the endogeneity dilemma in operations management research: theoretical, empirical, and pragmatic considerations. J. Oper. Manag. 52, 1–14.
Ketokivi, M.A., Schroeder, R.G., 2004. Perceptual measures of performance: fact or fiction? J. Oper. Manag. 22, 247–264.
Ketokivi, M.A., Schroeder, R.G., 2004. Strategic, structural contingency and institutional explanations in the adoption of innovative manufacturing practices. J. Oper. Manag. 22, 63–89.
Lawrence, P.R., Lorsch, J.W., 1967. Differentiation and integration in complex organizations. Adm. Sci. Q. 1–47.
Lawrence, T., Suddaby, R., Leca, B., 2011. Institutional work: refocusing institutional studies of organization. J. Manag. Inq. 20, 52–58.
Lee, J., Wu, F., Zhao, W., Ghaffari, M., Liao, L., Siegel, D., 2014. Prognostics and health management design for rotary machinery systems—reviews, methodology and applications. Mech. Syst. Signal Process. 42, 314–334.
Mcintyre, D.P., Srinivasan, A., 2017. Networks, platforms, and strategy: emerging views and next steps. Strateg. Manag. J. 38, 141–160.
Mckone, K.E., Schroeder, R.G., Cua, K.O., 1999. Total productive maintenance: a contextual view. J. Oper. Manag. 17, 123–144.
Milgrom, P., Roberts, J., 1995. Complementarities and fit strategy, structure, and organizational change in manufacturing. J. Account. Econ. 19, 179–208.
Miller, C.C., Washburn, N.T., Glick, W.H., 2013. Perspective—the myth of firm performance. Organ. Sci. 24, 948–964.
Miller, D., 1986. Configurations of strategy and structure: towards a synthesis. Strateg. Manag. J. 7, 233–249.
Miller, D., 1992. Environmental fit versus internal fit. Organ. Sci. 3, 159–178.
Molina-Azorín, J.F., 2014. Microfoundations of strategic management: toward micro–macro research in the resource-based theory. BRQ Bus. Res. Q. 17, 102–114.
Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., Ueda, K., 2016. Cyber-physical systems in manufacturing. CIRP Ann. - Manuf. Technol. 65, 621–641.
Roy, R., Stark, R., Tracht, K., Takata, S., Mori, M., 2016. Continuous maintenance and the future–foundations and technological challenges. CIRP Annals 65, 667–688.
Ruschel, E., Santos, E.a.P., Loures, E.D.F.R., 2017. Industrial maintenance decision-making: a systematic literature review. J. Manuf. Syst. 45, 180–194.
Sousa, R., Voss, C.A., 2008. Contingency research in operations management practices. J. Oper. Manag. 26, 697–713.
Suddaby, R., 2006. From the editors: what grounded theory is not. Acad. Manag. J. 49, 633–642.
Swanson, L., 2001. Linking maintenance strategies to performance. Int. J. Prod. Econ. 70, 237–244.
Swanson, L., 2003. An information-processing model of maintenance management. Int. J. Prod. Econ. 83, 45–64.
Thoben, K.-D., Wiesner, S., Wuest, T., 2017. Industrie 4.0" and Smart manufacturing - a review of research issues and application examples. Int. J. Autom. Technol. 11, 4–16.
Tonidandel, S., King, E.B., Cortina, J.M., 2018. Big data methods: leveraging modern data analytic techniques to build organizational science. Organ. Res. Methods 21, 525–547.
Tortorella, G.L., Vergara, A.M.C., Garza-Reyes, J.A., Sawhney, R., 2020. Organizational learning paths based upon industry 4.0 adoption: an empirical study with Brazilian manufacturers. Int. J. Prod. Econ. 219, 284–294.
Tracy, S.J., 2010. Qualitative quality: eight "Big-Tent" criteria for excellent qualitative research. Qual. Inq. 16, 837–851.
Tsang, A.H., 2000. Maintenance Performance Management in Capital Intensive Organizations. University of Toronto.
Van De Ven, A.H., Ganco, M., Hinings, C.R., 2013. Returning to the frontier of contingency theory of organizational and institutional designs. Acad. Manag. Ann. 7, 393–440.
Vermeulen, F., 2005. On rigor and relevance: fostering dialectic progress in management research. Acad. Manag. J. 48, 978–982.
Volberda, H.W., Van Der Weerdt, N., Verwaal, E., Stienstra, M., Verdu, A.J., 2012. Contingency fit, institutional fit, and firm performance: a metafit approach to organization–environment relationships. Organ. Sci. 23, 1040–1054.
Weiss, B.A., Pellegrino, J., Justiniano, M., Raghunathan, A., 2016. Measurement Science Roadmap for Prognostics and Health Management for Smart Manufacturing Systems.
Williamson, O.E., 1975. Markets and Hierarchies, p. 2630. New York.
Williamson, O.E., 1983. Credible commitments: using hostages to support exchange. Am. Econ. Rev. 73, 519–540.
Williamson, O.E., 1985. The Economic Institution of Capitalism. Free Press, New York.
Williamson, O.E., 1996. The Mechanisms of Governance. Oxford University Press.
Yoo, Y., Boland Jr., R.J., Lyytinen, K., Majchrzak, A., 2012. Organizing for innovation in the digitized world. Organ. Sci. 23, 1398–1408.