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Maintenance in digitalised manufacturing: Delphi-based scenarios for 2030

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ABSTRACT

Despite extensive research on future manufacturing and the forthcoming fourth industrial revolution (implying extensive digitalisation), there is a lack of understanding regarding the specific changes that can be expected for maintenance organisations. Therefore, developing scenarios for future maintenance is needed to define long-term strategies for the realisation of digitalised manufacturing. This empirical Delphi-based scenario planning study is the first within the maintenance realm, examining a total of 34 projections about potential changes to the internal and external environment of maintenance organisations, considering both hard (technological) and soft (social) dimensions. The paper describes a probable future of maintenance organisations in digitalised manufacturing in the year 2030, based on an extensive three-round Delphi survey with 25 maintenance experts at strategic level from the largest companies within the Swedish manufacturing industry. In particular, the study contributes with development of probable as well as wildcard scenarios for future maintenance. This includes e.g. advancement of data analytics, increased emphasis on education and training, novel principles for maintenance planning with a systems perspective, and stronger environmental legislation and standards. The scenarios may serve as direct input to strategic development in industrial maintenance organisations and are expected to substantially improve preparedness to the changes brought by digitalised manufacturing.

1. Introduction

The industrialised world is facing a fourth revolution through the realisation of digitalised manufacturing. This revolution, commonly triggered by the German initiative “Industrie 4.0” (Kagermann et al., 2013), builds upon computer science; information and communication technologies; and manufacturing science and technology to develop future manufacturing systems with three main characteristics: intelligent information acquisition; connectivity between system elements; and responsiveness to internal and external changes (Monostori et al., 2016). Porter and Heppelman (2014, 2015) describe how this revolution is radically reshaping companies and competition, and “creating the first true discontinuity in the organisation of manufacturing firms in modern business history” (2015, p. 31). The magnitude of this technological discontinuity will disrupt both the internal and external environment of manufacturing companies. Examples of internal changes are questioning and redefining classical organisational structures as a consequence of intensified coordination (Porter and Heppelman, 2015), and a need for future workforces with higher and more diversified competence profiles (Capgemini Consulting, 2015; Kagermann et al., 2013). Examples of external changes are the spurring of new market players, services, and business models (McKinsey and Company, 2015; The Boston Consulting Group, 2015; Roland Berger, 2015; Cisco, 2015; Capgemini Consulting, 2015), and issues with legislation, liability, and privacy of industrial data that puts pressure on re-inventing today's legal systems (DG Connect & EFFRA, 2015; PwC, 2015; Kagermann et al., 2013).

This revolution not only brings a technological discontinuity, but also a future in which the expectations on manufacturing systems are very high. In literature on digitalised manufacturing, expectations include substantial gains in productivity, significantly higher levels of automation, and drastic improvements in resource efficiency (The Boston Consulting Group, 2015; Roland Berger, 2015; PwC, 2015; Cisco, 2015; Deloitte, 2015; Capgemini Consulting, 2015). Monostori et al. (2016) acknowledge this view and explain that the expectations are manifold and include e.g. autonomous navigation, robustness at every level, remote and real-time control, predictability, efficiency and safety. In light of these expectations, it is evident that the advancements of digitalised manufacturing will dramatically increase the associated need for extraordinary maintenance management. However, it is rather remarkable that in both scientific and business literature on digitalised manufacturing, maintenance is barely even mentioned, or is perceived rather narrowly, with its scope seemingly confined to increased

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predictive maintenance and maintenance services (The Boston Consulting Group, 2015; Roland Berger, 2015; PwC, 2015; Cisco, 2015; Deloitte, 2015; Capgemini Consulting, 2015; Hermann et al., 2016; Kang et al., 2016; Wang et al., 2016; Thoben et al., 2017). When predictive maintenance is indeed under the spotlight, expectations include for example 30–50% reduction of total machine downtime (McKinsey and Company, 2015). Clearly, maintenance organisations have their work cut out for them in order to match this level of ambition.

At the same time, maintenance research has primarily approached digitalised manufacturing with a strong focus on technical advancements, e.g. data analytics (Lee et al., 2014), data-driven maintenance services (Herterich et al., 2015), remote-, predictive-, real-time-, and collaborative maintenance (Cannata et al., 2009; Muller et al., 2008), or envisioning highly reliable systems capable of surviving any form of disturbances (Lee et al., 2011). Lee et al. (2014) argue that self-maintenance must be achieved to meet the expectations of future manufacturing systems, but this technology is very far from realisation (Roy et al., 2016) and even the development of user-friendly industrial applications for predictive maintenance is lacking (Vogl et al., 2016). Roy et al. (2016) provide an extensive overview of technological challenges for future maintenance, but it is unfortunate that less emphasis has been put on simultaneously investigating how these technologies may influence organisational aspects, soft issues, and broader social aspects of maintenance organisations. Pellegrino et al. (2016) highlight the need to also consider the human element of maintenance in a digitalised environment, but a holistic picture of the future role of maintenance is far from complete. In sum, there is a lack of understanding of what the realisation of digitalised manufacturing entails for maintenance organisations along both hard (technical) and soft (social) dimensions.

The bottom line is that the recent advancements of digitalised manufacturing have spurred expectations on future manufacturing systems that dramatically increase the associated need for extraordinary maintenance management. At the same time, there is a lack of relevant, actionable guidance for industrial maintenance organisations to meet these expectations. In effect, there is an evident research gap between the expectations on digitalised manufacturing and the future role of maintenance, creating an urgent need to shed further light on this uncertain future. Fortunately, there is a method for closing this type of gap: scenario planning (Varum and Melo, 2010). Scenario planning forces firms to rethink their internal and external environment (Roubelat, 2006) and is especially useful when industry is about to experience significant change (Schoemaker, 1995), making it a particularly suitable methodology to systematically and holistically analyse the predicted disruptiveness brought by digitalised manufacturing.

Therefore, the aim of this paper is to close the gap between the expectations on digitalised manufacturing and the future role of maintenance by describing the most probable scenarios for maintenance organisations in the year 2030. These scenarios can serve as direct input to strategic development of maintenance organisations, which is expected to improve preparedness for digitalised manufacturing. Roy et al. (2016) have already posed the obvious research question for this gap: “How is maintenance going to change in this highly connected industrial environment?” (p. 682). This study provides answers to this question, specifically guided two formulated research questions that encompasses a holistic perspective on the research gap:

RQ1. *How will the internal environment (equipment, plant, and company level) of maintenance organisations change by 2030*?

RQ2. *How will the external environment (extra-company and environmental level) of maintenance organisations change by 2030*?

To contribute towards continuity in scenario planning research, the structure of the paper follows standard practices (e.g. Warth et al., 2013; Schuckmann et al., 2012; von der Gracht and Darkow, 2010). First, a literature review is presented in order to relate the study to existing knowledge; followed by description of the research methodology; and continued with presentation of results in terms of probable and wildcard scenarios. Thereafter, implications of the results for industry and academia are discussed; followed by proposals for further research; and ending with presentation of final conclusions.

2. Literature review

There are a number of extensive reports and articles that provide a holistic picture of the expectations on digitalised manufacturing. However, there is a lack of literature that specifically provides future scenarios for maintenance. In order to relate the present study to existing knowledge, it is therefore necessary to consider a combination of literature that examines the future of digitalised manufacturing at large, and the specific future of maintenance organisations. Since industrial decision support regarding the future touch upon multiple aspects that are rarely encompassed holistically by any empirical scientific study, many maintenance managers rely on forecasts from reputable business consultancy literature as well as scientific papers.

2.1. Expectations of digitalised manufacturing

A selection of recent business literature publications that provide a thorough description of fundamental concepts and overarching aspects of digitalised manufacturing are presented in Table 1. This literature was included in the development of projections in combination with numerous workshops and interviews with researchers and industrial experts (section 3.1). Although this type of literature consist mostly of industrial consultancy reports rather than scientific literature, these publications cover a broad scope of issues, have a significant audience among industrial management, and can be considered highly reputable. Within these publications, the most common research methods are surveys, interviews, and workshops. In fact, at the onset of this study (Fig. 1), there was no clear and comprehensive scientific body of literature covering digitalised manufacturing. Since then, scientific review papers on digitalised manufacturing have been published, which are presented in Table 2 and used to relate the results from this study to existing scientific knowledge (section 5).

According to the publications in Table 1, the current understanding of digitalised manufacturing is, at its core, mainly about technology. Further, this literature highlight very ambitious expectations of digitalised manufacturing. For example, the enabler of productivity gains, innovation and economic growth is data (Porter and Heppelman, 2014). Data is raised as the great resource of the next industrial era (Capgemini Consulting, 2015), and the value of data is further leveraged by horizontal and vertical integration of IT systems (Kagermann et al., 2013; The Boston Consulting Group, 2015; PwC, 2015). However, it is at the same time clear that the technology in factories of the future also impose social challenges. For example, manufacturing companies must develop a workforce with new and higher levels of competence (Capgemini Consulting, 2015) by attracting new talent (McKinsey and Company, 2015; Kagermann et al., 2013) whilst at the same time improving the existing workforce (Deloitte, 2015). This, in turn, creates a need for continuous education and training (DG Connect & EFFRA, 2015), put pressure on education systems (Kagermann et al., 2013), and require closer collaboration between industry and academia (Roland Berger, 2015). Making manufacturing a central part in the future of work means developing work environments that are technically efficient and socially sustainable: creative, flexible, safe, and welcoming to personal and professional development despite differences in competence, degrees, age, or culture (Deloitte, 2015; Capgemini Consulting, 2015; Kagermann et al., 2013). There is also a need to re-invent legal system to manage issues with legislation, liability, and privacy of industrial data (DG Connect & EFFRA, 2015; PwC, 2015; Kagermann et al., 2013). Digitalised manufacturing will also disrupt the business environment by spurring new market players, services, and business models (McKinsey and Company, 2015; The Boston Consulting Group, 2015; Roland Berger,

Table 1
Business literature publications on digitalised manufacturing included in the development of projections.

Author & Year	Type	Title & research details
McKinsey & Company (2015)	Consulting report	**Industry 4.0 – How to navigate digitization of the manufacturing sector** Based on a survey with more than 300 participants, interviews, and research, this study provides forward-looking statements on Industry 4.0.
The Boston Consulting Group (2015)	Consulting report	**Industry 4.0 – The Future of Productivity and Growth in Manufacturing Industries** Report describing the technological trends that serves as the building blocks of Industry 4.0, including examples from case studies in Germany.
Roland Berger (2015)	Consulting report	**The Digital Transformation of Industry** Commissioned by the Federation of German Industries and conducted by Roland Berger, this study involved 300 survey respondents and 30 interviews to explore causes and effects of digitalised manufacturing in European industry.
PwC (2015)	Consulting report	**The Smart Manufacturing Industry** Based on comments from more than 60 Swedish manufacturing companies, this report describes the potential and impact of digitalised manufacturing.
Cisco (2015)	Consulting report	**The Digital Manufacturer** Through a survey with more than 600 senior decision-makers in 13 countries, interviews, secondary research, and economic analysis, this study explores the business and organisational implications of digitalised manufacturing.
Deloitte (2015)	Consulting report	**Industry 4.0 – Challenges and solutions for the digital transformation and use of exponential technologies** With more than 50 participating Swiss manufacturing companies, this study aims to describe the key challenges in realising Industry 4.0.
DG Connect & EFFRA (2015)	Workshop report	**Innovation in Digital Manufacturing** Though a two-day workshop with over 50 participants from 13 member states within the European Commission, this report maps European initiatives for innovation in digitalised manufacturing and identifies areas of possible cooperation.
Porter and Heppelman (2015)	Harvard Business Review	**How Smart, Connected Products Are Transforming Companies** Article examining the impact of smart, connected products on companies' operational and organisational structures.
Porter and Heppelman (2014)	Harvard Business Review	**How Smart, Connected Products Are Transforming Competition** Article examining how smart, connected products are shifting competition in many industries, especially manufacturing.
Kagermann et al. (2013)	Working group report	**Recommendations for implementing the strategic initiative INDUSTRIE 4.0** Final report from the Industrie 4.0 working group with more than 70 contributing authors and 50 workshop participants, presenting recommended actions for realising Industry 4.0 in German manufacturing.

Table 2
Recent scientific literature on digitalised manufacturing.

Author & Year	Type	Title & research details
Thoben et al. (2017)	Journal paper	**"Industrie 4.0" and Smart Manufacturing – A Review of Research Issues and Application Examples** Review paper providing an overview of Industrie 4.0 and Smart Manufacturing, and identifying current and future issues in research, methodology and business.
Monostori et al. (2016)	Journal paper	**Cyber-physical systems in manufacturing** Review paper outlining the roots and expectations towards research and implementation of CPS in manufacturing, followed by highlighting related R&D challenges.
Hermann et al. (2016)	Conference paper	**Design Principles for Industrie 4.0 Scenarios** Based on quantitative text analysis and qualitative literature review, the paper aims to provide design principles for Industry 4.0 that are relevant for future research as well as developing industrial scenarios.
Kang et al. (2016)	Journal paper	**Smart Manufacturing: Past Research, Present Findings, and Future Directions** By surveying and analysing articles related to Smart Manufacturing, this paper identifies the past and present levels of Smart Manufacturing and tries to predict the future.

2015; Cisco, 2015; Capgemini Consulting, 2015; Porter and Heppelman, 2014, 2015). Clearly, digitalised manufacturing is a multi-faceted research problem that offer a broad palette of challenges for both society and academia; technological as well as social.

By now, digitalised manufacturing has become a top priority for research centres, universities, and companies. After the implementation of this study, a number of review papers have been published that provide a scientific perspective on digitalised manufacturing (Table 2).

From a scientific perspective, future manufacturing systems are expected to be robust and efficient and exhibit e.g. self-*X* capabilities, remote diagnosis, real-time control, and predictability (Monostori et al., 2016). To meet these high expectations, a number of challenges need to be addressed. Research challenges include but are not limited to: decision support systems to manage complex systems; standardisation; security; broadband infrastructure; data quality; regulatory frameworks; and human-machine symbiosis. Technological advancements needed are e.g. sensors, interoperability, data analytics, and additive manufacturing, and there are also business challenges such as privacy, investment limitations and coping with new business models and services (Thoben et al., 2017; Monostori et al., 2016; Hermann et al., 2016; Kang et al., 2016).

Comprehensive investigations of socio-ethical aspects of digitalised manufacturing are also needed (Monostori et al., 2016), and social challenges highlighted within this literature are e.g. training and education, and work organisation and design (Kang et al., 2016). From the combined literature in Tables 1 and 2, it is evident that digitalised manufacturing is a discontinuity that will bring a wide array of technological as well as social challenges. Monostori et al. (2016) claim that the potential of digitalised manufacturing is hard to underestimate, and that significant further research is needed in order to realise at least a portion of the partly exaggerated expectations.

2.2. Future maintenance management

In Table 3, a selection of scientific papers regarding future maintenance management is presented. These papers were included in the development of projections in combination with numerous workshops and interviews (section 3.1) and include publications addressing maintenance in digitalised manufacturing, or future practices and emerging trends within maintenance in general. This extensive empirical scenario study is the first of its kind within the maintenance realm and early to

Table 3
Literature on future maintenance management included in the development of projections.

Author & Year	Type	Title & research details
Herterich et al. (2015)	Conference paper	**The Impact of Cyber-Physical Systems on Industrial Services In Manufacturing** Paper exploring how Cyber-Physical Systems transform the service business in the equipment manufacturing industry and provide new opportunities beyond traditional maintenance.
Lee et al. (2014)	Conference paper	**Service innovation and smart analytics for Industry 4.0 and big data environment** Paper describing future trends of manufacturing service transformation in big data environment and the readiness of smart predictive tools for maintenance management.
Schmidt et al. (2014)	Conference paper	**Next Generation Condition Based Predictive Maintenance** Proposal of a framework for next generation predictive condition-based maintenance through the use of a variety of data in a cloud-based approach.
Lee et al. (2011)	Journal paper	**Self-maintenance and engineering immune systems: Towards smarter machines and manufacturing systems** Paper discussing state-of-the-art research in the areas of self-maintenance and engineering immune systems for machines in future manufacturing systems.
Cannata et al. (2009)	Conference paper	**Dynamic E-maintenance in the Era of SOA-Ready Device Dominated Industrial Environments** Paper discussing the needs and challenges for e-maintenance platforms in factories of the future.
Muller et al. (2008)	Journal paper	**On the Concept of e-maintenance: Review and current research** Review paper providing an overview of the current research and challenges within the field of e-maintenance.
Lee et al. (2006)	Journal paper	**Intelligent prognostics tools and e-maintenance** Paper outlining the field of e-maintenance and recent advancements of intelligent prognostics techniques, including results from several case studies.
Dunn (2003)	Conference paper	**The fourth generation of maintenance** Paper discussing the issues shaping the fourth generation of maintenance.
Peng (2000)	PhD thesis	**The post-maintenance era of complex equipment management in the semiconductor industry** Proposal of new alternatives to equipment management beyond the mainstream principles of maintenance management in the future microchip era of equipment.

address the research gap on maintenance in digitalised manufacturing. After implementation of this study (Fig. 1), scientific articles have been published on this specific topic (Table 4). This literature is used to relate the results to existing scientific knowledge (section 5).

A stringent focus on technical dimensions of maintenance management can be observed within the papers in Table 3. For example, the transformation towards digitalised manufacturing is expected to rely on predictive tools (Lee et al., 2014); data-driven design improvements and services; and remote diagnosis, predictions, and repair (Herterich et al., 2015). The field of e-maintenance emerged from the appearance of new IT and the need for integrating maintenance with other areas of the enterprise, and has largely focused on enabling four technology-driven maintenance strategies: remote-, predictive, real-time- and collaborative maintenance (Cannata et al., 2009; Muller et al., 2008). The vision of Engineering Immune Systems (EIS) is to design highly reliable systems capable of surviving any form of disturbances, made possible by utilising data and applying different modelling techniques (Lee et al., 2011).

Although these advancements along technical dimensions of maintenance undoubtedly hold great potential to improve future manufacturing systems, there is also a need to consider social implications brought by digitalised manufacturing at large (as described in section 2.1). For example, Dunn (2003) argue that future maintenance must also focus on applying organisational, systemic, and cultural controls to eliminate equipment failures. Similarly, Peng (2000) hypothesised on a vast array of social changes in regards to job objectives, organisational structures, psychosocial factors, and managerial expectations.

The top four papers in Table 4 provide both broad and detailed views of the future of Prognostics and Health Management (PHM) in the US, i.e. the collective term for health monitoring, diagnostics, prognostics and maintenance. There is an overlap in these publications, but the combined literature identifies several technological challenges that include but are not limited to: system-level analytics; effective and secure collection and translation of data into decision support; interoperability; data quality; diverging data formats and standards; lack of industrial awareness, experience and training in PHM; "self-*X*" capabilities; integration of old and new technology; retrofitting; business-cases for accelerating digitalisation; and lack of user-friendly PHM applications (Pellegrino et al., 2016; Jin et al., 2016; Vogl et al., 2016). Helu and Weiss (2016) specifically studied the current state of PHM in SMEs and identified four main barriers: lack of common data interfaces and protocols; lack of sufficient data; lack of security tools to protect sensitive information and intellectual property; and potential disruptions to operations.

The extensive review in Roy et al. (2016) is divided into three main

Table 4
Recent scientific literature on maintenance in digitalised manufacturing.

Author & Year	Type	Title & research details
Pellegrino et al. (2016)	Technical report	**Measurement Science Roadmap for Prognostics and Health Management for Smart Manufacturing Systems** Based on a road mapping workshop in Gaithersburg, Maryland sponsored by NIST, more than 60 experts from industry, government, laboratories and academia identified science challenges and R&D needs for PHM in a Smart Manufacturing context.
Jin et al. (2016)	Journal paper	**Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing** By means of surveys and case studies in US manufacturing firms, the paper examines the current practices of diagnostics, prognostics and maintenance and identified gaps, barriers, future trends and roadmaps for manufacturing PHM.
Vogl et al. (2016)	Journal paper	**A review of diagnostic and prognostic capabilities and best practices for manufacturing** Paper reviewing the challenges, needs, methods and best practices for PHM in manufacturing, with the aim of helping manufacturing systems becoming "smart" and realise the self-maintenance paradigm.
Helu and Weiss (2016)	Conference paper	**The Current State of Sensing, Health Management, and Control for Small-to-Medium-Sized Manufacturers** By means of several case studies, this paper specifically identifies needs, priorities, and constraints for PHM in manufacturing SMEs.
Roy et al. (2016)	Journal paper	**Continuous maintenance and the future – Foundations and technological challenges** Review paper presenting the foundations and technologies for maintenance in the future industrial product-service system context, including the role of IoT, standards and cyber-security within the Industry 4.0 context.

sections: foundations of continuous maintenance; technological challenges for the future; and maintenance in the industry 4.0 context. Six main foundations are identified (e.g. PHM and maintenance planning) for which several key technologies are necessary: non-destructive evaluation; repair technologies; prognostics; self-*X*; remote maintenance; digital MRO; big data analytics; and visualisation in maintenance task planning and training. In regards to these technologies, numerous challenges are identified, including e.g. robust RUL estimations; prediction of environmental impact; data quality; remote technologies; digital systems for managing data, information and knowledge; advancements of big data analytics; and augmented reality for maintenance support. Finally, specific challenges for maintenance in the industry 4.0 context are identified and include e.g. system-level maintenance planning; interoperability; IT security; long-term through-life data management; ownership of data; and human-machine collaboration.

Beyond technological challenges, Pellegrino et al. (2016) acknowledge that the next generation maintenance workforce will need new skills to effectively make use of modern technology and manage highly automated and complex systems. This requires education and training on multiple levels. Roy et al. (2016) frequently mention how new technology can reduce human errors and support human capabilities in a collaborative manner. In sum, this recent literature extends the stringent focus on technological challenges of future maintenance but also gradually acknowledge social challenges that are consistently highlighted in regards to digitalised manufacturing.

3. Methodology

Due to the apparent gap regarding the future of maintenance organisations, the high degree of uncertainty, and the magnitude of the technological discontinuity that is digitalised manufacturing, this study builds upon the long tradition and extensive research practices within scenario planning to contribute with systematic development of expert opinion consensus in an area that is essential for the realisation of digitalised manufacturing.

Scenario planning is particularly suited for assessing future developments, long-term planning and decision-making in uncertain situations (Varum and Melo, 2010). Scenarios provide straightforward contributions to industrial managers, e.g. helping people overcome cognitive inertia, accelerating organisational learning, effectively dealing with situations of strong agreement, and shielding organisations from the danger of groupthink and paralysis due to dissention (Bood and Postma, 1997). Further, scenarios question the prevailing mind-set (Schoemaker, 1995) and challenge strategic paradigms (Roubelat, 2006), thereby stimulating managers to consider changes that they would otherwise ignore. In addition, scenarios also provide contributions to the scholarly community. Ramirez et al. (2015) argues that scenarios help in critically consider existing assumptions and possible future developments of their field of study, and propose that scenarios can be used as a scholarly methodology to produce “interesting research”: research that develops theory, is innovative, less formulaic, and disconfirms assumptions held by those who read it; in the end being more likely to be read, understood, and remembered (Bartunek et al., 2006).

Scenario planning has been a popular methodological choice amongst scholars. Varum and Melo (2010) analysed 101 academic scenario studies from 1945 to 2005, where main themes included “product and service development” and “supply-chain management and logistics”. Nowack et al. (2011) specifically reviewed 24 Delphi-based scenario studies from 1988 to 2010, where frequent themes included energy, agriculture, and transportation. von der Gracht and Darkow (2010) presents a list of 18 scenario studies within the field of logistics alone. Strangely enough, to the best of our knowledge, an empirical scenario planning study within the field of maintenance management has never been done before, thereby making this study the first of its kind.

The Delphi method aims to systematically develop expert opinion consensus about future developments and events formulated as “projections” (short and concise future theses) (von der Gracht and Darkow, 2010), and is a valid and reliable method when executed with rigour in accordance to methodological guidelines (Landeta, 2006). Integrating the Delphi method in scenario planning (i.e. Delphi-based scenarios) can enhance the quality of the study in terms of creativity, objectivity, and credibility (Nowack et al., 2011). This study integrates the four characteristics of the well-recognized RAND Delphi method; anonymity, iteration, controlled feedback, and statistical group response (Dalkey and Helmer, 1963); to evaluate a total of 34 projections, as illustrated in Fig. 1.

The scenarios developed in this study are intended to maintain a holistic perspective on the manufacturing industry at all system levels, whilst being specific for maintenance organisations. To support this intent, a holistic system model was developed with inspiration from Kirwan's (2000) soft-systems framework for understanding human-factors-related interactions and interfaces in socio-technical systems. The framework describes a “nested” systems view of an organisation, which helps to position possible interactions from a “lowest” technical level up to an environmental level. Since this framework rest upon the premise that technological implementations must integrate into an existing socio-technical system to be successful, adapting it to the study at hand provides a particularly suitable model for supporting the development of future maintenance scenarios in a holistic manufacturing context. The adapted holistic model (Fig. 2) is divided into two main areas (internal and external environment) and five levels (equipment, plant, company, extra-company, and environment level), and supported the overall, conceptual framing of this research (e.g. as a mediating tool during workshops and categorising projections in the Delphi survey). The contents of all system levels within the model are illustrated and explained in Fig. 2.

In order to stimulate new thinking and develop scenarios that are not constrained by existing strategic plans within maintenance organisations, an effective planning horizon of 14 years (to 2030) was chosen. Within the business literature in Table 1, there is a concentration on 10–15 years

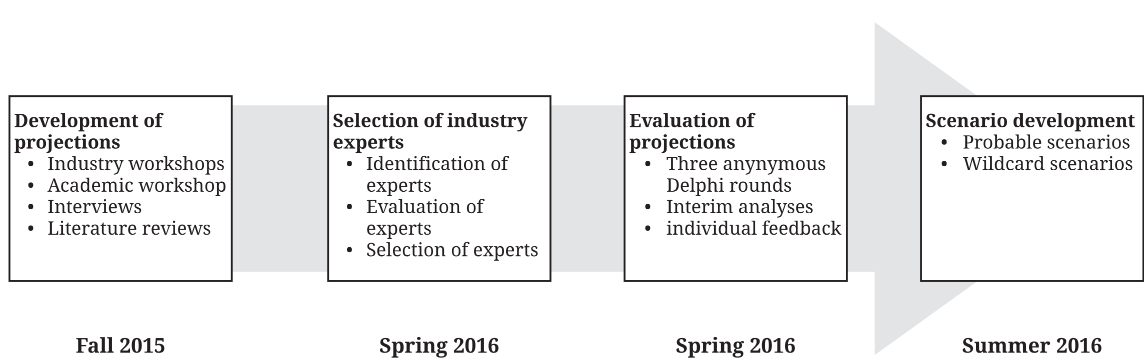

Fig. 1. Scenario planning research process.

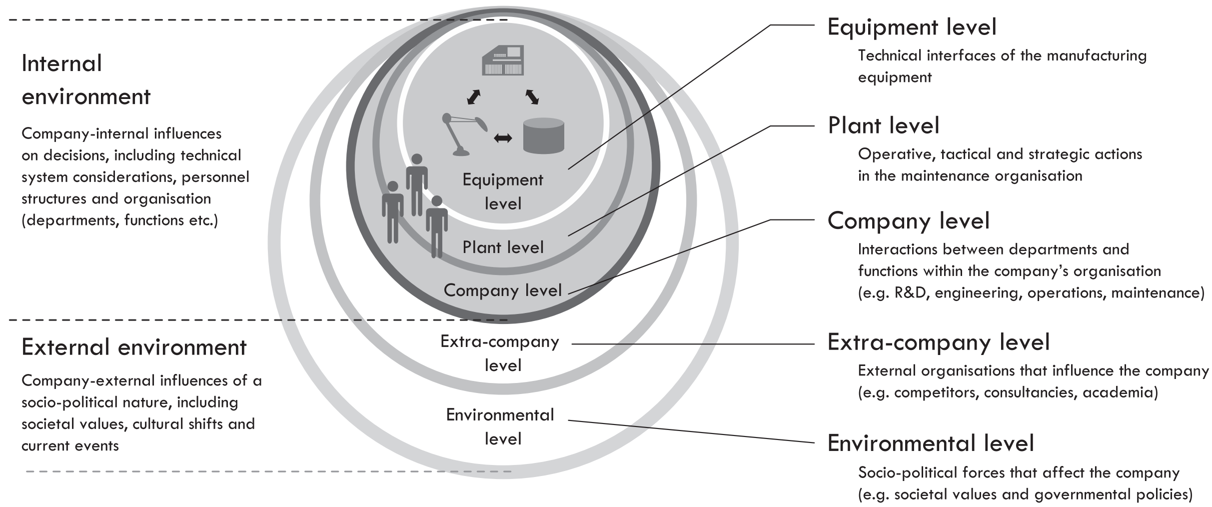

Fig. 2. Holistic model with different system levels; based on Kirwan's (2000) model.

as the expected time frame for the realisation of digitalised manufacturing. This choice also aligns well with similar scenario studies, where e.g. Ecken et al. (2011) analysed 6 studies with an average planning horizon of 16 years, von der Gracht and Darkow (2010) cited 18 studies with an average of 17.8 years, and the review in Nowack et al. (2011) revealed an average of 15.5 years for comparable studies.

3.1. Development of projections

The process of developing projections consisted of three main phases: data collection, coding, and formulation and validation (Fig. 3).

First, four main data sources where used in the data collection phase. These sources complemented each other in order to cover all aspects of maintenance in digitalised manufacturing: (1) Three industrial workshops were held in the three largest cities in Sweden. A total of 30 participating industrial experts participated in brainstorming sessions and discussions on future developments for maintenance organisations. (2) An academic workshop was held with four maintenance researchers, who identified and mapped potential developments for maintenance organisations until 2030 using the KJ-method (Kawakita, 1991) and the holistic model (Fig. 2) as a mediating tool. (3) Six interviews were conducted with researchers in various fields relevant to digital manufacturing: economic geography, decision support for economics, ecological and social sustainability in manufacturing, information strategies in manufacturing, and manufacturing technology. The holistic model (Fig. 2) acted as a mediating tool to identify potential developments for maintenance organisations until 2030. (4) A literature review was conducted spanning two main publication forms: recent digitalised manufacturing reports (Table 1), and scientific publications on future maintenance (Table 3). Attempts to define a "4th generation" of maintenance practices have been published since the 2000's (e.g. Dunn (2003) or Manickan (2012)). However, consensus has not been achieved, and relevant literature from this decade was therefore identified to find inspiration about future developments of maintenance. The selection was limited to scientific research, with an emphasis on high-level holistic papers such as reviews and descriptions of overall concepts.

Second, these four sources of data were imported into a qualitative data management software (NVivo 11). Building on well-established practices in qualitative research, a coding phase was initiated using grounded codes and constant comparison. In contrast to a-priori codes, grounded codes concentrate on finding new themes that emerge from the data. Constant comparison was used to ensure consistency in coding, which involve comparing every selection and coding of a passage of text with all previous codes (Corbin and Strauss, 1990). This coding phase resulted in 34 main themes that emerged from the data.

Third, 34 projections (short and concise future theses) were initially formulated based on the data within each main theme. After this formulation, Bradfield et al.'s (2005) advice for face validation was followed, which revolves around four common baseline criteria: coherence, plausibility, internal consistency, and logical underpinning. Specifically, a face validation procedure was developed based on the following criteria: appropriate number of elements in each projection description

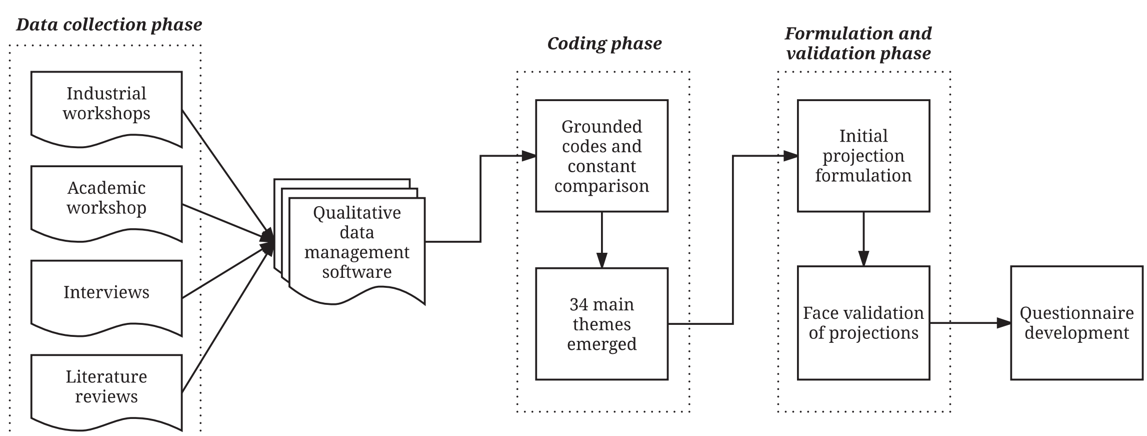

Fig. 3. Process of developing projections.

(Salancik et al., 1971, p. 68), clear definition of scientific or technological concepts (Johnson, 1976), avoidance of ambiguity (Rowe and Wright, 2001), and elimination of conditional statements (Lovedridge, 2002). Two external researchers independently validated the projections, and two additional researchers separately reviewed the projections with the sole focus on potential ambiguity in sentence formulations. The complete list of all 34 projections are presented in Table 5.

The questionnaire was developed based on generic survey design guidelines (Blair et al., 2014). To ensure reliability and improve the design, three external researchers and two industrial representatives participated in a pilot test. The final questionnaire incorporated the same structure as the holistic model (Fig. 2).

3.2. Selection of industry experts

A panel size of 25 experts was chosen for this study based on general recommendations of 20–30 participants in Delphi research (Parente and Anderson-Parente, 1987). Since rigorous selection of experts in Delphi research is a necessity for validity and reliability (Hasson and Keeney, 2011; Landeta, 2006), a standardised three-stage procedure was adopted from previous research: (1) identification of potential experts, (2) evaluation of identified experts, and (3) expert recruitment (see e.g. Schuckmann et al., 2012; von der Gracht and Darkow, 2010).

First, an initial pool of 50 potential experts was created based on information on the largest companies in Swedish manufacturing (Swedish Standard Industrial Classification, SE-SIC 2007). Second, the appropriateness of each candidate was evaluated. A total of 19 expert evaluation criteria were identified from a set of previous studies (Warth et al., 2013; Schuckmann et al., 2012; Ecken et al., 2011; von der Gracht and Darkow, 2010). Building on these criteria, the potential experts were evaluated on the basis of (1) position and responsibilities within the company, (2) knowledge and experience within the field, and (3) willingness and time to participate. Third, through emails and personal phone calls, experts were invited to participate in the study based on the evaluation.

The panel predominantly consisted of maintenance managers at strategic level. In total, 20 participants (80%) were representatives from

Table 5
Complete list of projections.

No.	Projections at different system levels
Equipment level	
1	Much of the existing equipment is complemented and upgraded with sensors and connectivity to interact and communicate with new technology.
2	Different types of data (e.g. physical, condition, events, context) from different sources and times are analysed together in order to detect patterns.
3	New, smart equipment has built in intelligence and makes its own decisions, e.g. through self-monitoring, self-diagnostics, self-optimisation, and self-maintenance.
4	Modern equipment is more modularised, making maintenance actions simpler and more effective (e.g. replacing entire modules instead of single components).
5	Equipment contains more software and a large focus for maintenance organisations is software maintenance.
6	Data are stored and analysed in the cloud, where all necessary information is accessible anywhere, anytime.
7	Standards for integration of information systems (e.g. CMMS, MES, PLM) have been developed and implemented in industry.
8	Enormous amounts of data are generated from the equipment, and maintenance puts great emphasis on identifying and analysing the right data to make the right decisions.
Plant level	
9	Maintenance employees have new and higher levels of competence, where both digital competence (e.g. IT, data analytics, systems, cloud) and social competence (e.g. communication, networking, interdisciplinary collaboration) are needed.
10	To secure necessary competence, maintenance puts greats emphasis on continuous education and training of the workforce to keep up with technological developments.
11	Maintenance attracts driven and competent individuals through a challenging, creative, and safe work environment, with career opportunities and flexible working conditions that allow for a balance between work and private life.
12	Daily decision-making within maintenance is decentralised, meaning that individuals have responsibility, authority, and autonomy to make their own decisions based on data.
13	Fact-based decisions are the foundation for maintenance planning, particularly with the help of decision support based on predictive and prescriptive data analytics.
14	New technology, data and analysis methods enable “smart work”, e.g. real-time online monitoring and control, or remote inspection and repair.
15	Maintenance puts less emphasis on reactive/preventive maintenance and more on technological development, e.g. failure elimination, upgrades, and reconfiguration of equipment for new product requirements and generations.
16	New digital tools are used within maintenance, e.g. augmented reality for remote guidance, maintenance simulation, and 3D-printing of spare parts.
17	Maintenance is planned based on insights from individual machines (e.g. conditions, alarms) combined with a systems perspective (e.g. bottleneck detection) with the aim of optimising the performance of the entire manufacturing system.
Company level	
18	All organisational functions are integrated through open and transparent sharing of data, where maintenance collaborates closely with e.g. operations, IT, engineering, R&D, and purchasing.
19	Open and transparent sharing of data between factories enables close collaboration, internal benchmarking, and sharing of best practices in maintenance within the company.
20	The maintenance department has vanished and has been replaced by a cross-functional organisation (maintenance, engineering, purchasing etc.) where teams deliver manufacturing as a service (e.g. OEE, uptime) throughout the manufacturing systems' life-cycle.
21	The perception of maintenance has changed, so that maintenance has high status within the organisation, internally proselytising on technological development, and participates in more top management teams.
22	Maintenance has embraced a larger role with responsibility and authority to drive technological development throughout the manufacturing systems' life-cycle.
23	Maintenance has a zero-failure vision and works towards the goal of delivering economical, ecological, and social sustainability.
Extra-company level	
24	New business models for maintenance services have been developed through sharing of data, e.g. complete solutions with the goal of delivering value over time ("product-as-service", availability, uptime).
25	New unique types of maintenance services are offered thanks to sharing of data, e.g. remote maintenance, virtual expert support, cloud-based real-time monitoring, predictive analytics, optimisation, and upgrades.
26	To secure the access to competence, expert knowledge and technology within maintenance, close partnerships with vendors (e.g. machine- or service vendors) are established throughout the manufacturing system's life-cycle.
27	The market for maintenance services is co-ordinated in digital platforms where customers and vendors are connected, share data, and co-ordinate individual services.
28	Various actors (e.g. manufacturers, machine vendors and service providers) share data and collaborate in digital networks on knowledge, competence, and new technology regarding maintenance.
29	Industry works closely with academia (e.g. colleges and universities) to develop and secure the new competence required within maintenance.
Environment level	
30	New actors have emerged in the maintenance market, which has led to increased competition and selection among maintenance services (e.g. specialist enterprises with expert knowledge on sensors, data analytics and specific maintenance actions).
31	Cyber attacks are a real threat towards both connected machines and personal data, making data security a central focus for maintenance organisations.
32	Legislation regarding digitalisation has not kept up with the technological development, hindering development within maintenance, e.g. liability issues when sharing data.
33	Maintenance is visible in the social debate and influences e.g. legislation, policies, and the development of standards.
34	Stronger environmental legislation and standards (e.g. CO_2-emissions, energy consumption) have increased the pressure on maintenance, which is expected to ensure that equipment meet environmental requirements.

top 100 largest manufacturing companies in Sweden (in terms of no. of employees). In fact, more than half of them (56%) represented a company within the top 20. The participants represented companies with both discrete (e.g. automotive, aerospace, bearings) and continuous (e.g. paper & pulp, chemistry, refinery) manufacturing. Out of the 25 experts, 18 (72%) were maintenance manager, 4 (16%) reliability engineering manager, whereas the remaining 3 (12%) experts were CEO or manager for outsourced maintenance. A vast majority of the experts have extensive experience within the maintenance field: on average more than 20 years (Fig. 4):

3.3. Evaluation of projections

Throughout the three Delphi rounds, each projection was evaluated in terms of probability, impact, and desirability. Probability (EP) was estimated in percentages from 0-100%, whilst impact (I) and desirability (D) were estimated on ordinal 5-point Likert scales (1: Very low, 5: Very high). In addition, the experts were instructed to support their estimates of probability and impact with written arguments. These arguments allowed for a more in-depth understanding of the experts view, such as if the impact is expected in terms of increased productivity or changing work environment. Impact was only evaluated in the first round since previous researchers have argued that experts are unlikely to modify such assessments (e.g. von der Gracht and Darkow, 2010). The total duration of the Delphi survey was eight weeks, consisting of three Delphi rounds and two interim analyses. The time interval of each Delphi round was two weeks, and the time interval of each interim analyses was one week.

In-between each Delphi round, interim analyses were conducted in order to provide individual feedback to each expert. Based on the feedback, experts had the possibility to revise their answers and provide additional arguments in the subsequent rounds. The feedback consisted of statistical group responses in the form of standard deviation and a box plot illustrating the mean and inter-quartile range (IQR) for probability, and the median for impact and desirability. In addition, written arguments were summarised using open coding (Corbin and Strauss, 1990) and provided to the experts, which also allowed for a check of potential misunderstandings. Potential outliers were identified using modified Z-scores, which is appropriate with sample sizes of 10–40 as used in this study (Iglewicz and Hoaglin, 1993). Focus was given to situations where more than 1% of the data had an absolute value of 3.5 or higher (Field, 2005; Iglewicz and Hoaglin, 1993).

Since distorted feedback can negatively influence Delphi results (Scheibe et al., 1975), two specific measures were taken to ensure the validity of each analysis step. First, the quantitative sets of data from each Delphi round was continuously shared with an external researcher that independently replicated the statistical analyses. Second, the qualitative data analyses were continuously monitored and validated by an additional researcher.

In von der Gracht's (2012) extensive review on consensus measurement in Delphi research, the importance of testing for both stability and level of agreement as stopping criterion between Delphi rounds is highlighted. Therefore, due to the dependent samples in this study, group stability was tested first using a paired *t*-test (Weir et al., 2006) in combination with Cohen's d for effect size (Cohen, 1988), where projections with $p > 0{,}05$ and $d < 0{,}2$ were considered stable. Thereafter, due to the high value of consensus or dissent for data interpretation in scenario development, the level of agreement was tested using IQR, where consensus was considered for projections with an IQR ≤ 20 (e.g. Rayens and Hahn, 2000; Raskin, 1994; Scheibe et al., 1975). Consequently, all 34 projections were evaluated in the first two rounds, and 19 stable but dissent projections were included in the third round. The analysis and interpretation of quantitative results (Table 6) were based on the experts' final round estimates, i.e. round two for 15 projections and round three for 19 projections (von der Gracht, 2012).

The Delphi method can improve the quality of probability estimates for future events, but is not always capable of completely eliminating what is known as “desirability bias”: experts assess desirable events as more probable, and undesirable events as less probable (Rowe and Wright, 1996). By analysing data from six Delphi surveys, Ecken et al. (2011) clearly demonstrates how desirability bias is decreased but not necessarily eliminated throughout the Delphi process. Consequently, they (Ecken et al. 2011) propose a post-hoc procedure to identify projections that are likely to carry the effect of desirability, and quantify the consequences of desirability bias on final results. In this study, we apply this proposed post-hoc procedure in order to control for desirability bias, an analysis that act as a complement to traditional Delphi results.

Several observations can be made that indicates a high level of commitment and involvement from the experts. First, every expert participated in all three Delphi rounds (0% dropout rate). Second, only 10 missing answers were detected out of 5200 expected estimations of probability, impact, and desirability (missing value rate < 0,2%). Third, a total of 2716 individual free text arguments were submitted in regard to probability and impact. Finally, telephone interviews were conducted with all participants after the final round, in which all expressed a general

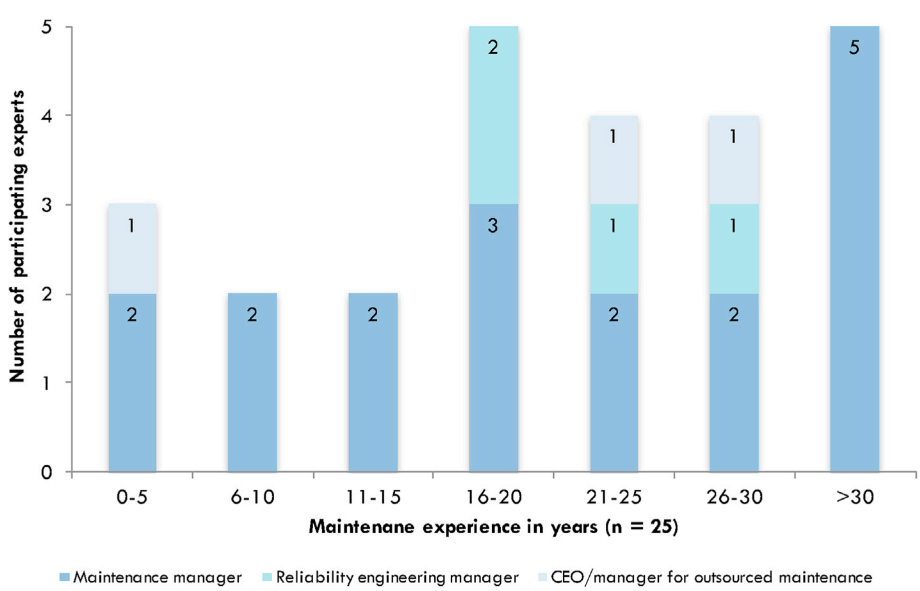

Fig. 4. Demographic information of participating experts.

satisfaction of the survey content, questionnaire design, and feedback. Together, this lends substantial support for the collected data to be of high quality.

3.4. Development of scenarios

From the experts' evaluation of projections, two types of future scenarios for maintenance were identified. First, probable scenarios were identified as projections with high probability and consensus amongst experts, which provide insights on the most probable future of maintenance. Second, wildcard scenarios were identified as projections with lower probability but still substantial impact, which are essential in scenario development. They provide insights on future events that are less likely to occur, but could potentially have large impact on the industry (Grossmann, 2007).

4. Results

The results from the Delphi survey are presented in this section, including desirability bias analysis and the development of probable and wildcard scenarios.

4.1. Quantitative results for Delphi projections

Delphi statistics are presented in Table 6, which shows the experts' evaluations of probability, impact, and desirability for all 34 projections. In addition, it illustrates the convergence in probability estimates and development of consensus.

To support interpretation of Table 6, an example is provided for projection #17 – "Maintenance planning with a systems perspective", one of the projections identified as a probable scenario (section 4.3). The projection was evaluated with a mean probability of 76% in round one, 77% in round two, and 80% in round three, i.e. a positive mean change of 5. The standard deviation decreased from 24 to 14 from round one to three, i.e. a negative SD change of 45, which demonstrates a convergence of the experts' probability estimates. An IQR of 15 (in brackets) in the third and final round indicates consensus in probability estimates (IQR $\leq$ 20). Finally, the projection was evaluated with a median impact of 4 in the first round ($k = 1$) and a median desirability of 4 in the final round ($k = 3$).

By analysing final round estimates, the data in Table 6 reveals that all projections have a median impact of 3 or higher, and a vast majority have an estimated probability of more than 50%. This confirms that the research process (Fig. 1) resulted in the development and selection of relevant projections, and supports the notion that all 34 projections are important to consider in industry and academia. In addition, by continuously monitoring outliers using modified Z-scores (see section 3.3), it was observed that accounting for outliers affects neither stability nor the development of consensus, demonstrating that the Delphi process provided robust results (which corroborates previous studies, e.g. Warth et al., 2013).

The underpinning rationale of the Delphi method is clearly illustrated in the data: a convergence of the experts' opinions. This is indicated by the decrease in standard deviation (SD change) for all projections. The

Table 6
Delphi statistics.

Projection no. & short title	Round 1			Round 2			Round 3			Mean change	SD change	I (k = 1)	D (k = 2,3)
	Mean	SD	IQR	Mean	SD	IQR	Mean	SD	IQR				
Equipment level													
1. Equipment upgrades	66	26	45	69	20	25	72	14	(20)	9	−47	4	4
2. Data analytics	82	16	(16)	82	14	(10)				0	−9	4	4
3. Machine intelligence	63	22	25	64	19	27	64	16	22	3	−28	4	4
4. Modularisation	72	21	39	73	16	25	73	12	(13)	1	−43	4	5
5. Software maintenance	69	24	40	67	20	(19)				−2	−15	4	3
6. Cloud computing	68a	28	45	63	23	30	62	22	(16)	−8	−23	3	3
7. Interoperability	76	18	23	76	13	(15)				0	−30	4	4
8. Big data management	70	23	36	75	16	24	77	12	(10)	10	−48	4	4
Plant level													
9. Digital and social competence	69	20	30	71	12	(15)				3	−41	4	4
10. Education and training	77	19	34	80	14	(20)				3	−25	4	4
11. Work environment	62	23	25	65	16	25	68	12	(15)	10	−47	4	5
12. Decentralised decision-making	68	28	40	70	23	28	71	20	(19)	4	−29	4	4
13. Fact-based maintenance planning	76	14	20	76	10	(10)				0	−28	4	4
14. Smart work procedures	77	20	25	79	13	(18)				2	−37	4	4
15. Maintenance improvements	57	20	(16)	60	15	(16)				5	−25	4	4
16. Digital tools	67	22	43	69	18	(16)				3	−18	4	4
17. Maintenance planning with a systems perspective	76	24	28	77	21	25	80	14	(15)	5	−45	4	4
Company level													
18. Organisational integration	65	24	40	69	18	(12)				7	−28	4a	4
19. Internal benchmarking	71	26	33	74	20	30	74	14	(20)	4	−46	4	4
20. Maintenance department	39	25	35	40	20	(20)				3	−20	4	3
21. View on maintenance	64	27	30	66	22	(20)				3	−19	4	4
22. Enlarged maintenance function	63	21	45	63	18	25	65	13	(10)	3	−40	4	4
23. Zero failure vision	67	28	31	69	22	28	70	17	26	4	−38	4	4
Extra-company level													
24. Business models	61	28	38	63	24	23	63	19	(20)	3	−31	3a	3a
25. Maintenance services	70	26	30	68	23	24	68	22	(11)	−3	−17	4	4
26. Partnerships	68	19	40	67	17	23	69	15	(18)	1	−20	4	4
27. Digital market	50	24	(20)	52	20	32	56	15	23	11	−39	3	3
28. Digital networks	45	24	33	43	18	(17)				−3	−22	3	3
29. Industry and academia	69	22	44	72	18	(15)				4	−21	4	4
Environmental level													
30. New actors	68	28	50	67	21	25	70	15	(15)	3	−45	4	4
31. Cyber attacks	70	28	53	68	24	33	69	18	(19)	−2	−36	4	3
32. E-jurisprudence	63a	30	26	61	25	34	61	19	25	−3	−37	3a	2
33. Maintenance in social debate	43	23	(20)	45	19	(15)				4	−19	3	4
34. Environmental legislation and standards	83	24	(20)	80	25	22	78	16	(15)	−5	−32	4	4

Note: Brackets indicates consensus, i.e. IQR $\leq$20; a indicates $n = 24$.

weakest convergence is observed for projection #2 – Data analytics (SD change = −9), whilst the strongest convergence is found for projection #8 – Big data management (SD change = −48). In fact, the average SD change is −31. Further support for this rationale is shown by the achievement of consensus for almost all projections. After three rounds, consensus is achieved for 30 out of 34 projections, and 5 projections already achieved consensus in the first round. Together, this implies that the iteration and controlled feedback in three Delphi rounds resulted in an increase of experts' agreement over time.

The holistic model (Fig. 2) enables a number of interesting observations of the Delphi statistics (Table 6), especially in regard to the distribution of results across the model. First, a vast majority of the high probability projections (EP > 75%) belong to the two lowest levels of the internal environment, whilst two thirds of the low probability projections (EP < 50%) are found in the external environment. Second, all strong consensus projections (IQR = 10) are located in the lower spectra of the internal environment, whilst half of the dissent projections (IQR > 20) are located in the external environment. Third, the external environment holds a higher proportion of projections assessed towards lower levels of desirability. Together, these three observations led us to believe that future developments in the external environment of maintenance organisations might not only be harder for the experts to assess, but could also include specific aspects that are met with particular caution.

4.2. Desirability bias analysis

Table 6 shows that a majority of the projections are desirable, indicated by a total of 26 projections being assessed with D ≥ 4. In fact, low desirability is only observed for one projection (#33). This provides tentative support to the notion of a probable future also being a desirable future. To investigate this notion further, the post-hoc procedure proposed by Ecken et al. (2011) is applied, which identifies and quantifies the extent of desirability bias. The original publication provides full modelling details. In short, experts' final estimates are used to first logistically regress EP on D to identify a group of significantly biased projections. Thereafter, a second linear regression is conducted for biased projections to obtain new average probabilities adjusted for individual desirability bias. The results of the post-hoc procedure are summarised in Table 7, which shows adjusted probabilities (EP Adj.) and adjusted level of agreement (IQR Adj).

The results in Table 7 show that 20 out of 34 projections are significantly affected by desirability bias. Interestingly, all biased projections are over-estimated (thus the negative direction of EP change). One projection experiences a change of tendency in probability estimates when controlling for desirability bias (#15). Further, controlling for desirability bias only change the level of agreement in three projections (i.e. change of tendency in IQR). In one projection (#27), the desirability bias impeded the achievement of consensus. In the other two (#15 and #33), consensus was achieved because their probability estimates were affected by desirability bias. The remaining 17 biased projections remained their level of agreement (i.e. consensus with IQR <20). In fact, half of the biased projections had an IQR too high.

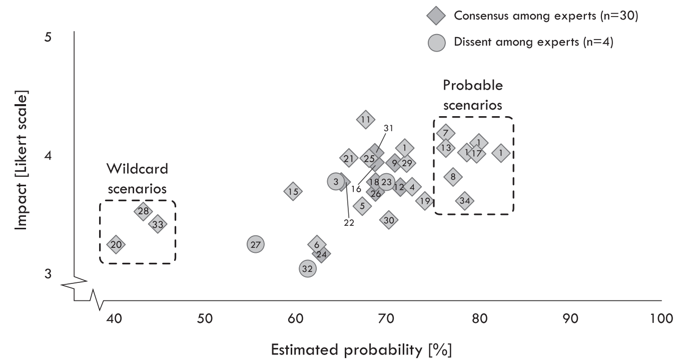

Fig. 5. Impact - probability scatter plot.

4.3. Scenarios for 2030

The most probable scenarios for maintenance organisations are founded on the cluster of projections with high estimated probability (EP ≥ 75%) and consensus among the experts, as visualised in Fig. 5. Note that Fig. 5 shows impact in terms of mean instead of median to allow for an easier interpretation of the visualised data. In total, this cluster includes eight high impact projections (I = 4), including three (#2, #8, #13) with strong consensus (IQR = 10). Based on the experts' comments throughout the three Delphi rounds, qualitative descriptions of the probable scenarios are presented in Table 8, including the most common arguments for high and low probability along with a final conclusive narrative.

4.4. Wildcards

In contrast to the probable scenarios presented in section 4.3, so called wildcards are typically perceived as eventualities with low

Table 7
Desirability bias analysis based on Ecken et al. (2011).

Projection no.	EP Final	IQR	EP Adj,	IQR Adj.	IQR change	EP change
1. Equipment upgrades	72	20	57	13	−33	−20
4. Modularisation	73	13	62	15	19	−15
5. Software maintenance	67	19	65	18	−7	−2
6. Cloud computing	62	16	59	16	−3	−4
9. Digital and social competence	71	15	56	15	−3	−21
12. Decentralised decision-making	71	19	60	18	−8	−16
14. Smart work procedures	79	18	64	15	−17	−19
15. Maintenance improvements	60	16	49	23	41	−19
16. Digital tools	69	16	57	18	13	−17
20. Maintenance department	40	20	39	19	−3	−3
22. Enlarged maintenance function	65	10	50	10	0	−22
24. Business models	63	20	58	11	−43	−8
25. Maintenance services	68	11	56	16	44	−17
26. Partnerships	69	18	59	11	−39	−15
27. Digital market	56	23	50	20	−13	−10
28. Digital networks	43	17	41	18	3	−4
29. Industry and academia	72	15	57	13	−13	−21
30. New actors	70	15	63	12	−17	−10
33. Maintenance in social debate	45	15	38	22	44	−16
34. Environmental legislation and standards	78	15	67	15	0	−14

Table 8
Probable scenarios, including arguments for high and low probability and final conclusive narratives (scenarios elaborated with qualitative Delphi input).

No.	Probable scenarios at different system levels	
Equipment level		
2	**Data analytics** Different types of data (e.g. physical, condition, events, context) from different sources and times are analysed together in order to detect patterns.	
	High probability Data collection (DC) is pervasive today, and the development of technology and software that supports data analytics will continue in the future. Data will be collected and analysed automatically in the future. Lower cost of DC and development of data analytics and decision support accelerate this development. DC and analytics are an important way of working in complex processes and high-priority equipment. Data analytics from combined sources provide an overall picture of the manufacturing system and enable identification of patterns and root causes for equipment status and performance.	**Low probability** Difficult to motivate in the short-term. Too expensive to implement in simple equipment.
	Conclusion: Further developments of data analytics will enable maintenance organisations to effectively use data as decision support in 2030. The value of data analytics will lie in the ability to identify patterns and root causes and take proactive action to avoid disturbances and failures, thereby increasing productivity. This value will increase dramatically when several types of data are integrated, e.g. historical and real-time condition monitoring data, event data, and context data from the whole product population over time. The primary challenge will be economical justification.	
7	**Interoperability** Standards for integration of information systems (e.g. CMMS, MES, PLM) have been developed and implemented in industry.	
	High probability Standards are a necessity to manage information in large manufacturing systems, e.g. collecting data from different equipment types, coordination and communication between all equipment in central systems, and managing different information systems from different equipment vendors. The work to develop standards has been initiated and implementation will therefore be reached by 2030.	**Low probability** The work with developing and implementing standards is too slow and will lag behind. Strong competition and a wide selection of information systems limits the possibility to agree on common standards.
	Conclusion: Standards will be necessary in order to reap the benefits of digitalised manufacturing since they enable interoperable information systems and thus horizontal and vertical integration. For maintenance organisations, interoperability standards enable integration of manufacturing equipment and information systems from different vendor platforms. Interoperability removes the constraint of adhering to proprietary platforms, thereby relaxing the need to buy unique equipment for specific demands. Challenges in reaching common standards by 2030 will include competition and unwillingness to abandon current proprietary systems.	
8	**Big data management** Enormous amounts of data are generated from the equipment, and maintenance puts great emphasis on identifying and analysing the right data to make the right decisions.	
	High probability There will be enormous amounts of data, but the challenge lies in assuring competence, resources, and decision support systems to analyse it. The possibility to collect and analyse large amounts of data provide new possibilities to make better decisions in maintenance. Future decision support systems will automatically analyse data, making data analytics simple without the need for analysis personnel. A necessity for maintenance data analytics is to secure the data quality through a structured DC process, thereby only sorting and analysing relevant and correct data.	**Low probability** Due to limitations in time and human resources, a prerequisite is that maintenance systems automatically analyse data and present decision support.
	Conclusion: In 2030, manufacturing equipment will generate large amounts of data, which hold great potential as decision support in maintenance. However, data only has value when used, which require the development of competence, resources and systems that enable maintenance organisations to make use of their data. Maintenance organisations will use data that adds value and enables decision-making, and will not waste time and resources on structuring, sorting, and prioritising of irrelevant data. Therefore, challenges will include achieving high quality maintenance data and developing maintenance management systems that automatically transform big data into decision support.	
Plant level		
10	**Education and training** To secure necessary competence, maintenance puts greats emphasis on continuous education and training of the workforce to keep up with technological developments.	
	High probability It is a necessity to manage future competence requirements and maintain competitiveness. New technology requires competence development. Education and training is prevalent today and will likely increase with new competence requirements. Changing competence profiles will require education and training.	**Low probability** It is uncertain whether top management realise the importance of education and training, or whether the organisation will dedicate the time required.
	Conclusion: In order to be competitive in 2030, continuous education and training will be an absolute necessity. The rapid development of digital technology demands that the competence profile of maintenance employees evolve at the same pace. Failure to develop a maintenance workforce that can effectively utilise the technology in future factories will increase the sensitivity to disturbances, decrease the responsiveness to failures, and reduce competitiveness. Challenges includes communicating the need for education and training to top management as well as developing new innovative ways of training: e.g. skills assessment and monitoring, best practice experiences, and utilising ICT tools.	
13	**Fact-based maintenance planning** Fact-based decisions are the foundation for maintenance planning, particularly with the help of decision support based on predictive and prescriptive data analytics.	

(*continued on next page*)

Table 8 (*continued*)

No.	Probable scenarios at different system levels	
	High probability A clear trend today that will increase in the future. Fact-based decisions is a key enabler for improving maintenance planning. A natural development alongside increased automation, interoperability of signals and systems, and improved data analysis methods. Will be an important complement to traditional maintenance practices.	**Low probability** Requires the development of better and more user-friendly tools, methods, and systems for decision support.
	Conclusion: In 2030, maintenance organisations will have abandoned traditional ad-hoc planning and embraced fact-based planning. Predictive maintenance in 2030 predicts when disturbances and failures will occur. Supported with estimations of remaining useful life, maintenance organisations can base their planning on monitoring and prognostics rather than fault identification and diagnostics. Prescriptive maintenance in 2030 complements the prediction of disturbances and failures by also suggesting the most suitable counter-action. The economic impact will be substantial as fact-based planning increases availability, extends the life span of equipment, and enables more cost-effective maintenance with fewer resources. The main challenge will be to incorporate predictive and prescriptive data analytics in user-friendly decision support systems.	
14	**Smart work procedures** New technology, data and analysis methods enables "smart work", e.g. real-time online monitoring and control, or remote inspection and repair.	
	High probability The technology is already available today and will be increasingly utilised in the future with improved tools, methods, and services. Enables reduction of response times and repair lead-time and provide information to employees on-site. There are no doubts regarding the technology, but the challenge lies in organisational aspects, collaboration with vendors, and standardised communication protocols.	**Low probability** Inspection and repair will be performed on-site since they require physical actions.
	Conclusion: The adoption of digital technology is already advanced, and by 2030 these technologies will be utilised in smart maintenance organisations that are predominantly proactive. Real-time maintenance enables continuous monitoring of equipment performance and status, thereby enabling an overview of the manufacturing system and the ability to swiftly respond to disturbances and failures. Remote maintenance enables the provision of maintenance from anywhere, thereby reducing maintenance response times and repair lead-times. The challenge will not be building the technology, but rather getting people to use it properly and creating an organisation that fosters new ways of working.	
17	**Maintenance planning with a systems perspective** Maintenance is planned based on insights from individual machines (e.g. condition, alarms) combined with a systems perspective (e.g. bottleneck detection) with the aim of optimising the performance of the entire manufacturing system.	
	High probability This approach is already prevalent today, but will be improved in the future through new technology and better decision support systems. Enables maintenance to be planned with a flow perspective, where maintenance efforts are directed to achieve maximum effect on reliability and availability. Focus on overall manufacturing system performance is a necessity for competitiveness.	**Low probability** Appealing in theory but difficult in practice, especially in smaller companies.
	Conclusion: By 2030, maintenance planning will not be driven by the requirements of individual machines, but rather by the needs of the entire manufacturing system. Maintenance planning with a systems perspective aims at simultaneously maintaining multiple (similar or dissimilar) pieces of equipment in a manufacturing system so that maintenance efforts optimise the performance of the entire system. This planning principle can e.g. be manifested through differentiation and prioritisation of maintenance activities to the current manufacturing system constraint (i.e. bottleneck). The value of this principle will be the ability to maximise the effect from limited maintenance resources. The main challenge will be to develop and implement methods and algorithms in maintenance decision support systems that are useful in practice.	
Environment level		
34	**Environmental legislation and standards** Stronger environmental legislation and standards (e.g. CO_2-emissions, energy consumption) have increased the pressure on maintenance, which is expected to ensure that equipment meets environmental requirements.	
	High probability This trend is already prevalent - environmental requirements will increase and become more influential on maintenance in the future. These requirements will increase for all organisational functions, including maintenance. New technology will be useful in meeting environmental requirements, e.g. online monitoring and control of energy consumption.	**Low probability** The environmental impact is primarily determined in the design phase.
	Conclusion: Maintenance organisations are already under pressure to meet environmental requirements today, but these requirements will continue to rise in importance by 2030. Since high equipment reliability is a necessity to comply with legislation and standards, maintenance will play a central role in achieving environmental sustainability. Promoting environmental sustainability in maintenance can also be of economic value as sustainable manufacturing companies may have a competitive advantage in 2030. Digital technology will aid maintenance organisations in meeting environmental requirements, e.g. through monitoring and prediction of energy consumption and failures causing high CO_2-emissions. The challenge will lie in raising the awareness of how maintenance contribute to sustainable manufacturing, e.g. improving resource efficiency, increasing life-length of equipment and reducing energy use, waste and emissions.	

probability and potentially high impact (Grossmann, 2007). Due to the lack of a strict definition of wildcards, we take inspiration from the logic utilised in von der Gracht and Darkow (2010), who identified potential wildcards with for example EP = 42%; I = 1.8; IQR = 20. Therefore, we direct particular attention to the cluster of projections with lower estimated probability: #20 – "Maintenance department" (EP = 40%; I = 4), #28 – "Digital networks" (EP = 43%; I = 3), and #33 – Maintenance in social debate (EP = 45%; I = 3). All three projections are consensually assessed as less probable ($IQR \leq 20$) and with medium or high impact ($I \geq 3$). In addition, two of them are neutrally desirable (D = 3 in #20 and #28), suggesting them to be neither a threat nor an opportunity, whilst one (#33) is in fact the only undesirable projection (D = 2). These scenarios are important since they provide companies with possible future situations that are less likely to occur, but are still necessary to prepare for (von der Gracht and Darkow, 2010). Since providing full qualitative descriptions of wildcards scenarios are beyond the scope of this paper,

Table 9
Wildcard scenarios with promoting and hindering forces.

No.	Wildcard scenarios at different system levels	
Company level		
20	**The maintenance department has vanished and been replaced by a cross-functional organisation (maintenance, engineering, purchasing etc.) where teams deliver manufacturing as a service (e.g. OEE, uptime) throughout he manufacturing systems' life-cycle.**	
	Promoting forces	**Hindering forces**
	Cross-functional teams with shared goals and common development resources can reach both broader and higher levels of competence.	Maintenance will need to remain as a separate department in order to ensure specific maintenance competence and resources, and to prevent maintenance from becoming a function with unclear roles and responsibilities. The maintenance department will remain, but will increase its cross-functional collaboration with other functions in order to broaden its competence profile. This type of organisational change requires large amounts of time and effort, since it challenges cultural barriers and conventional hierarchies.
Extra-company level		
28	**Various actors (e.g. manufacturers, machine vendors and service providers) share data and collaborate in digital networks on knowledge, competence, and new technology within maintenance.**	
	Promoting forces	**Hindering forces**
	This type of collaboration could change the entire business strategy for some companies. With a changed world economic system, various actors could collaborate instead of solely compete for business.	This will be prevented by one factor above all else: competition. Data, information, knowledge, products, services and trade secrets are all regarded as competitive advantages and/or "hard currency" that will not be shared between companies. The risks of sharing data are too large: secrecy policies and a difficulty in knowing who has access to the data slows this development. There is a difficulty in achieving obvious mutual benefits for all involved parties.
Environment level		
33	**Maintenance is visible in the social debate and influences e.g. legislation, policies, and the development of standards.**	
	Promoting forces	**Hindering forces**
	The importance of maintenance in public infrastructure will be highlighted in the social debate; on the one hand its positive influence on profitability, safety etc., and on the other hand the cost of poor maintenance. The societal status of maintenance as a discipline determines its visibility in the social debate; factors that raise its status include increased research and clear organisation of maintenance issues. An increased understanding of the role of maintenance in achieving sustainability can improve the possibilities for maintenance to be visible in the social debate.	Other societal problems will dominate the social debate.

these are presented in Table 9 with promoting and hindering forces based on the experts' comments.

5. Discussion

This Delphi-based scenario planning study aimed to describe the most probable scenarios for maintenance organisations in future digitalised manufacturing, guided by two research questions regarding how the internal and external environment of maintenance organisations will change by 2030. Through a three-round Delphi survey with 25 maintenance experts in Swedish manufacturing industry, a total of 34 projections (Table 5) were evaluated in terms of their probability, impact, and desirability (Table 6). The Delphi survey resulted in a convergence of the experts' opinion, illustrating a high level of agreement in their final estimates. In fact, 30 projections reached consensus, out of which 4 experienced particularly strong consensus. Moreover, a vast majority of the projections were assessed with a high median impact and an estimated probability of more than 50%. In sum, this study contributes with a long list of potential future developments with great relevance to both industry and academia.

As the main aim of this study, a total of eight probable scenarios for maintenance organisations were developed (Table 7). These scenarios describe the most probable future for maintenance in digitalised manufacturing by 2030. Seven dominant themes are highly likely to influence the internal environment of maintenance organisations: data analytics, interoperable information systems, big data management, emphasis on education and training, fact-based maintenance planning, new smart work procedures, and maintenance planning with a systems perspective. Moreover, one dominant theme is highly likely to influence the external environment: stronger environmental legislation and standards. Thus, the highly probable future of maintenance organisations is data-driven, facts-based, embedded with smart technology, fuelled by a strong emphasis on continuous development of the workforce, and in accordance to stronger environmental requirements.

In contrast to the probable scenarios, this study also included the development of wildcard scenarios: future events that are less likely to occur, but could potentially have large impact on maintenance organisations (Grossmann, 2007). A total of three wildcards were identified and described: the vanishing maintenance department, collaboration in digital networks, and maintenance visibility in social debate (Table 8). Although limited in their scope, these wildcards provide further insight on less expected developments for maintenance organisations until 2030.

During the interim analyses of the iterative Delphi evaluations, it was observed that the anonymous discussions between participating experts at times spanned across several projections. This resulted in that the experts' comments and succeeding scenarios (Table 7) may be perceived as similar, but are in fact distinctively different. For example, data analytics refers to the integrated analysis of various data types at different levels; big data management refers to the challenges of transforming large amounts of data into decision support; and fact-based maintenance planning refers to the change from current ad-hoc planning to future fact-based planning.

For the industrial management audience, this study provides results that can be directly applied by maintenance managers. We suggest managers to use the eight probable scenarios as direct input to strategic development (Schoemaker, 1995). Specifically, they should be used as support in defining long-term strategies for the realisation of digitalised manufacturing, thereby improving maintenance organisations' preparedness to the disruptiveness of digitalised manufacturing. Despite the concentration of probable scenarios within the internal environment, we also encourage managers to use the results of this study to evaluate and potentially rethink their external environment (Roubelat, 2006). Ultimately, the scenarios will stimulate managers to consider changes that they would otherwise ignore.

For the scientific community, this study considers scientific literature in regards to both a general digitalised manufacturing context and a maintenance-specific context. Most of the challenges identified in literature published after the implementation of this study (Table 4) are in fact covered. The 34 projections; developed through workshops, interviews and literature reviews (Fig. 2); encompass the vast majority of the topics in these publications, which strengthens the relevancy of the projections. In particular, most of the eight probable scenarios (Table 7) are also supported by these studies, e.g. data analytics; big data management; interoperability; maintenance planning with a systems perspective; and meeting environmental requirements by using e.g. prediction of environmental impact (Pellegrino et al., 2016; Jin et al., 2016; Vogl et al., 2016; Helu and Weiss, 2016; Roy et al., 2016).

Further, this study specifically considers several existing assumptions and future developments in maintenance research. Research along technical dimensions of maintenance (Lee et al. 2011, 2014; Cannata et al., 2009; Muller et al., 2008; Lee et al., 2006) must also consider the requirements of the users. As described in several of the probable scenarios (section 4.3), data-driven fact-based decisions will be the future of maintenance practices, but decision support systems should ideally provide automatic results, be simple, and user-friendly. This pledge for user-friendly analytics applications is strengthened with the claim by Vogl et al. (2016) and highlight that this issue needs to be addressed in maintenance research. One example could be to internally or externally package data collection and analysis into a common decision support service for the end user. However, this demands that current problems with e.g. data quality and diverging data formats and standards are resolved. These problems are especially highlighted in the probable scenario big data management (#8) and supported by recently published literature (Pellegrino et al., 2016; Jin et al., 2016; Vogl et al., 2016; Helu and Weiss, 2016; Roy et al., 2016).

This study goes beyond the technology-dominant maintenance literature (Tables 3 and 4) and firmly fortifies the fact that the future of maintenance also holds a vast array of challenges along social dimensions, e.g. competence (#9), education and training (#10), and work environment (#11). The future maintenance workforce will need higher and broader level of competence, which must be supported with continuous education and training on multiple levels; a notion reinforced by Pellegrino et al. (2016). Further, we observed several concerns regarding the external environment that have relevance to research into maintenance services. Connectivity is expected to break down company borders and increase transparency (Herterich et al., 2015), and a prerequisite for data-driven maintenance services is a system where data is shared and integrated (Muller et al., 2008). However, according to this study, there seem to be a resistance within maintenance organisations to leave the traditional system of closed borders and instead embrace a system of open relationships. The participating experts express competition and data security as major hinders to industrial collaboration, and show a permeating concern for the risks involved in sharing data throughout the value chain. These challenges regarding data security, privacy, liability, and ownership of data is also supported by recent literature and therefore deserve intensified attention (Table 4).

Although this study is specifically focussed on maintenance, the results also relate to scientific literature on digitalised manufacturing in general (Table 2). Beyond security and privacy issues (Monostori et al., 2016; Kang et al., 2016), it is also clear from this study that architectural features such as horizontal and vertical integration through interoperability (Thoben et al., 2017; Hermann et al., 2016) need to maintain a company-wide perspective that also includes maintenance applications (Roy et al., 2016). Further, socio-ethical aspects (e.g. competence, training and education) need to be addressed across all domains and organisational functions (Kang et al., 2016). In regards to such overarching challenges, knowledge sharing across domains and interdisciplinary research are needed. However, from the perspective of making an impact beyond the maintenance realm, it is primarily hoped that this paper has demonstrated the importance of maintenance for realising digitalised manufacturing and effectively meeting the expectations on future manufacturing systems.

Over-optimism on the future of maintenance is observed among the participating experts. As a whole, we interpret this optimism among maintenance managers as a desire to break the historical pattern of under-prioritising and ignoring the importance of maintenance, and instead increase the status, expand the role, and professionalise the maintenance function. This, in turn, could result in maintenance receiving the attention on strategic management level it deserves. An optimistic outlook on the future of maintenance is further supported by Jin et al. (2016), and with an extended perspective, this could also reflect how the potential of digitalised manufacturing is hard to underestimate and that expectations of digitalised manufacturing are at least partly exaggerated (Monostori et al., 2016). This observation was enabled by desirability bias analysis, which showed that 20 out of 34 projections were significantly biased; all over-estimated (Table 7). Note that adjusting for desirability bias does not necessarily concern the accuracy of the probability estimates. Instead, it is a way of understanding possible systematic bias in the data and support better decision-making on the basis of Delphi results (Ecken et al., 2011).

This scenario planning study deployed the well-proven Delphi method in the evaluation phase, which have been previously utilised and recommended (Nowack et al., 2011). Moreover, specific measures to ensure validity and reliability were taken throughout the research process (Fig. 1). Particular emphasis was put on contributing to continuity in scenario planning research by adhering to methodological guidelines proposed in literature (e.g. von der Gracht, 2012; Ecken et al., 2011; Bradfield et al., 2005). However, as with all empirical research, there are limitations of this study that provide guidance for further research. The focus on the largest companies within the Swedish manufacturing industry exhibit two obvious forms of continuation. First, extending the geographic scope to also include companies in other countries, which is relevant since there the scenarios in this study are supported by outlooks on future maintenance in US manufacturing (Pellegrino et al., 2016). Second, extending the study to also include small- and medium sized companies, which is relevant since differences in digital technologies and strategies in maintenance between large companies and SMEs have been identified (Jin et al., 2016). Moreover, the sample size of 25 participants follows general recommendations (Parente and Anderson-Parente, 1987), but further studies could include larger samples by using more advanced data collection methods, e.g. a web-based real-time Delphi (Gnatzy et al., 2011). As the main aim of this study was to describe the most probable scenarios for maintenance organisations, in-depth analysis of differences amongst the groups of participants were excluded, e.g. industrial branches. The experts' comments throughout the study provided some indication of such differences, and this could certainly be a topic for future research. Finally, the complete set of 34 projections (Table 5) provide general guidance for future research directions in maintenance, and the experts' comments (Tables 8 and 9) can be used to identify and target specific research challenges.

6. Conclusions

The recent advancements of digitalised manufacturing have spurred expectations on future manufacturing systems that dramatically increase the associated need for extraordinary maintenance management, creating a research gap between the expectations on digitalised manufacturing and the future role of maintenance. This study fills this gap by contributing with descriptions of the role of maintenance in future digitalised manufacturing along both hard (technical) and soft (social) dimensions.

This is achieved through the first empirical Delphi-based scenario planning study within the maintenance realm. Specifically, this study contributes with systematic development of expert opinion consensus about maintenance in digitalised manufacturing through an extensive three-round Delphi survey with 25 maintenance experts at strategic level from the largest companies within the Swedish manufacturing industry. Relevant descriptions are captured in 34 projections about potential changes of the internal and external environment for maintenance organisations by 2030. By developing eight probable scenarios, this study describes the most probable future for maintenance organisations in digitalised manufacturing. These scenarios provide answers to the two research questions:

RQ1. *How will the internal environment (equipment, plant, and company level) of maintenance organisations change by 2030*?

Conclusions: Seven dominant themes are highly likely to influence the internal environment of maintenance organisations: data analytics, interoperable information systems, big data management, emphasis on education and training, fact-based maintenance planning, new smart work procedures, and maintenance planning with a systems perspective.

RQ2. *How will the external environment (extra-company and environmental level) of maintenance organisations change by 2030*?

Conclusions: One dominant theme is highly likely to influence the external environment: stronger environmental legislation and standards, where maintenance organisations are expected to ensure that equipment meets environmental requirements.

This study also describes three wildcard scenarios: future events that are less likely occur but could potentially have substantial impact on maintenance organisations. Further, despite the concentration of probable scenarios within the internal environment, this study contributes with notions of concerns amongst maintenance practitioners within the external environment: hesitance towards sharing data throughout the value chain, the limiting factor of competitiveness between parties in industrial collaboration, and a permeating worry for data security. Such concerns impose several challenges for maintenance research and the application of future maintenance services.

Above all, this study provides substantial managerial contribution. The eight probable scenarios can be used as direct input to strategic development of maintenance organisations by supporting in defining long-term strategies for the realisation of digitalised manufacturing. The long list of potential future developments captured in 34 projections support industrial maintenance managers in evaluating and potentially rethinking their internal and external environment. This can increase the preparedness to the disruptiveness of digitalised manufacturing, thereby enabling the exploitation of opportunities and resolving of challenges within maintenance management in future manufacturing systems.

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