Big Picture of Next Generation Manufacturing

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Abstract In our real-time Delphi survey, we present 24 projections for Next Generation Manufacturing. An international set of experts from multiple fields, e.g., engineering, information systems, social sciences, and management, evaluated these projections regarding their likelihood and their impact on manufacturing firms by the year 2030. The experts predict that in the coming decade, we will see a significant increase in the use of production data in the form of digital shadows, which will in turn shape both internal and external processes of manufacturing companies. The quantitative results of the Delphi study show that there is significant disagreement among the experts about the likelihood and impact of several of the projections. The most likely projection is the increased importance of environmental sustainability, while the least likely is the emergence of a central platform provider for Next Generation Manufacturing. The most impactful projections are those related to the roles of digital services, data sharing, hybrid intelligence, and environmental sustainability.

[Abstract generated by machine intelligence with GPT-3. No human intelligence applied.]

1 Overview

In our real-time Delphi survey, we present 24 projections for Next Generation Manufacturing. An international set of experts from multiple fields, e.g., engineering, information systems, social sciences, and management, evaluated these projections regarding their likelihood and their impact on manufacturing firms by the year 2030. The final list of projections is provided in Table 1. The projections are

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clustered according to the framework adopted from Gawer (2014), whereby projections (P1)–(P6) belong to the *governance* dimension, (P7)–(P13) to *organization*, (P14)–(P17) to *capabilities*, (P18)–(P21) to *interfaces*, and (P22)–(P24) to the additional dimension of *resilience*. The projections were initially developed by interdisciplinary workshop groups and were subsequently refined and filtered based on a pre-test with a group of 13 experts (for more details on the methodology, see chapter "Applying the Real-Time Delphi Method to Next Generation Manufacturing").

Out of a total of 35 experts from the industry and academia, 29 completed the survey in full, while 6 completed the survey in part. All projections were assessed by 17 to 23 experts from the industry and by 12 experts from the academia. Each projection received ratings from 21 to 26 experts from Germany and from 8 or 9 experts from the rest of the world. This resulted in a total of 1930 quantitative estimations which were further supported by 629 qualitative arguments. As a result, we give an overview of Next Generation Manufacturing based on the experts' quantitative assessments.

2 Expert Assessments

Overall, the experts' assessments of the projections show that the role of digital shadows in production by 2030 is still the subject of controversial debate (see Table 1). To determine whether the experts reached a consensus in estimating the probability of a projection, we used the interquartile range (*IQR*) of their estimates. To improve comparability with prior reports of Delphi studies in the literature, we downscaled the percentage estimates by dividing them by 10 before calculating the *IQR*s and used an *IQR* of 2 or less as the criterion for consensus (see, e.g., Jiang et al., 2017; Scheibe et al., 1975; von der Gracht, 2012; von der Gracht & Darkow, 2010). Based on this threshold, the experts reached a final consensus on the probability of only 4 of the 24 projections developed. The topics on which the experts agreed are the role of subscription models for production machinery (P1), the reduction of labor through AI-based software and robots (P13), the increasing importance of environmental sustainability of production (P15), and the decentralization of supply chains (P22). The experts concurred that the increased role of environmental sustainability is particularly likely (67%), while for the other three projections, they consistently indicated medium probabilities (between 52% and 58%). The projections that resulted in the highest level of dissent between the experts are the emergence of a central platform provider as the operating system for the Industrial Internet of Things (P4), the mediating role of platforms for data sharing (P5), the implementation of adequate measures for protecting employees' privacy (P12), and plant management from home (P21). For all four of these projections, the probability estimates yielded *IQR*s equal to or greater than 4.

Figure 1 displays the average estimates for probability and firm impact for all 24 projections. Starting by focusing on the probability dimension, the projections

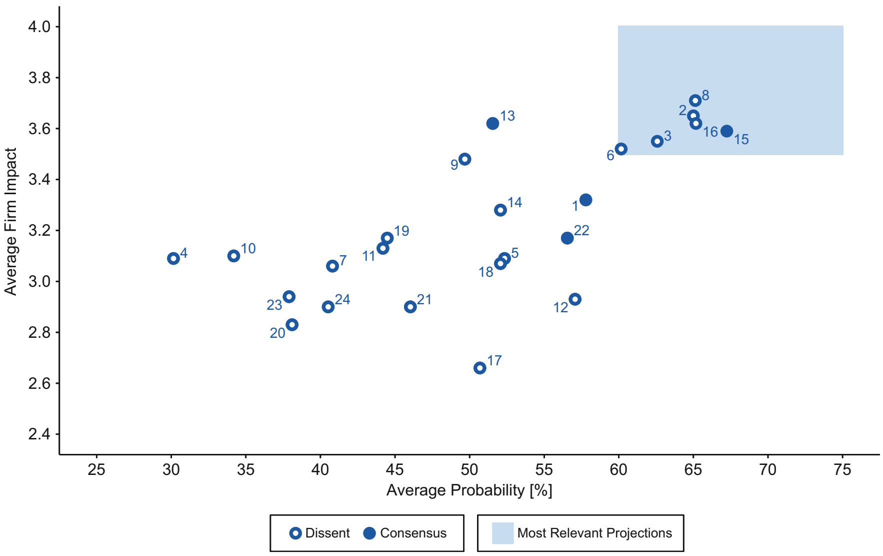

Fig. 1 Expert assessments of 24 projections for Next Generation Manufacturing

show a wide spread of average estimated probabilities, ranging from 30% to 67%, with a mean (*M*) of 52% and a standard deviation (*SD*) of 11%. Closely following the projection on environmental sustainability (P15), which was estimated to be the most likely, the next most likely projections are the rising importance of digital services (P2), hybrid intelligence (P8), and full transparency of production systems based on digital twins (P16), all with an estimated probability of 65%. In contrast, the experts considered the emergence of a central platform provider for Next Generation Manufacturing (P4: 30%) and the upheaval of current management structures by virtue of AI-based decision systems (P10: 34%) to be the least likely to occur by 2030. Regarding the potential impact of the projections on firms, the experts' average ratings on the 5-point scale varied between 2.66 and 3.71 ($M = 3.22$, $SD = 0.30$). Consistent with their high probability ratings, projections (P2) and (P8) also received the highest average impact scores (3.65 and 3.7), whereas the development of new multidisciplinary university degree programs (P17: 2.66) and the possibility for production workers to operate their workstations from home (P20: 2.83) are expected to have the lowest impact on manufacturing companies.

Considering the estimates of both probability and firm impact, six projections that the experts consider the most relevant for the future of production emerge. They are highlighted by the colored area in Fig. 1. The rationale for using the selected post hoc cut-off values of probability estimates above 60% and firm impact ratings above 3.5 is that the resulting 6 projections are assessed as being more likely than any of the other 18 projections and represent 6 of the 7 most impactful projections. The only projection that has a higher estimated firm impact than some of the six selected projections is rated as considerably less likely. Therefore, the results of this Delphi study emphasize the importance of considering the increasing role of digital services (P2), the benefits of sharing usage and production data with business partners (P3), the development of industrial data protection regulations (P6), the role of hybrid intelligence in production decision-making (P8), the environmental sustainability of production (P15), and the full transparency of production systems based on digital twins (P16) in the strategic planning of production firms and in related future research.

3 Comparison Between Subgroups of Experts

Although the further analysis and discussion of the expert assessments in this book focus on the full expert sample, we present here some additional insights into the experts' perspectives by comparing the assessments of different types of experts. Figure 2a illustrates the differences in assessments between academic and industry experts. When calculating the *IQRs* of the probability estimates for consensus identification within the subgroups, both groups show a consensus for projection (P15), consistent with the findings for the full sample. However, both groups also yielded a consensus for projection (P4), which yielded one of the highest levels of dissent when looking at the full sample. The observed dissent can thus be attributed to the different perspectives of the two groups of experts, which are internally consistent, with academics estimating a higher probability than industry representatives. The academics also yielded a consensus on the probability of introducing collaborative robots in production (P7).

While the mean average probability ratings of the academic ($M = 53\%$, $SD = 10\%$) and industry ($M = 50\%$, $SD = 11\%$) experts are similar, experts from the academia rated 17 of the 24 projections as more likely than their industry counterparts. That said, a Wilcoxon signed-rank test did not show a significant difference in the probability ratings between the two groups ($p = 0.056$, $r = 0.275$). Individual projections that are considered more likely by the academics include the introduction of collaborative robots (P7), the disruptive effect of AI-based decision systems on established leadership structures (P10), and the decentralization of supply chains (P22). In contrast, the industry experts attributed a higher probability to the implementation of digital shadows of production workers (P11) and the introduction of adequate anonymization procedures for the protection of employees' personal rights (P12) than the academic experts. Regarding the firm impact ratings, academics ($M = 3.30$, $SD = 0.33$) and industry members ($M = 3.19$, $SD = 0.34$) also yielded similar mean average rating, with the academics rating the firm impact of the projection higher than industry members in 15 of 24 cases. The difference between the ratings of the two groups was again not significant

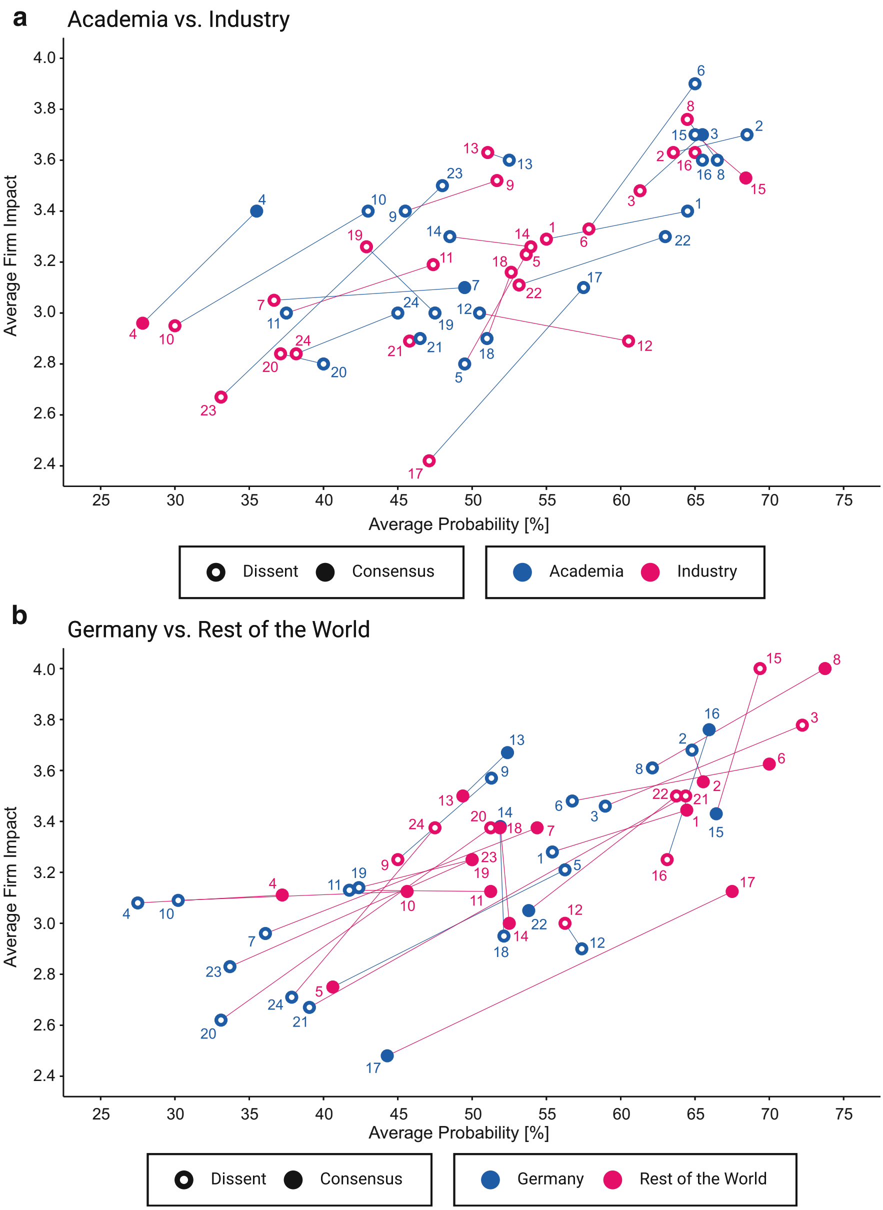

Fig. 2 Expert assessments of 24 projections for Next Generation Manufacturing differentiated between experts from the academia and from the industry (**a**) and between experts from Germany and the rest of the world (**b**). The connecting line between the two assessments for each projection is colored according to the group with the higher probability rating

($p = 0.145$, $r = 0.210$). The largest differences between the two groups, corresponding to higher impact assessments by the academic experts, are for the projections of new multidisciplinary university degree programs (P17) and increasing production costs due to more regional production and higher inventory levels (P23). Conversely, the industry experts considered the introduction of platforms as mediators in data sharing (P5) in particular as more impactful than the academic experts.

Switching to the comparison between experts from Germany and from the rest of the world (see Fig. 2b), this division of the full expert sample highlights the higher levels of consensus among the experts within the respective subsamples. Whereas the German experts yielded a consensus for projections (P13), (P15), (P16), (P17), and (P22), the experts from other countries did so for projections (P1), (P2), (P4), (P5), (P6), (P7), (P8), (P10), (P11), (P13), (P14), (P17), (P18), and (P23). This observation may indicate the importance of experts' regional background and cultural experiences for their predictions on the future of production. However, the small sample sizes of the subsamples should be considered, as they affect both the informative value of the *IQR* as a measure of dispersion and the overall generalizability of the inferred conclusion.

In terms of probability estimates, the experts from Germany ($M = 49\%$, $SD = 12\%$) showed a lower mean average estimation than the other experts ($M = 57\%$, $SD = 10\%$), providing lower estimates for 18 of the 24 projections. Based on the performed Wilcoxon signed-rank test, this difference between the average probability estimates of the two groups reaches statistical significance ($p < 0.01$, $r = 0.456$). Future developments that the German experts consider particularly less likely are the introduction of new multidisciplinary university degree programs (P17) and plant management from home (P21). In contrast, the emergence of platform providers as mediators for data sharing (P5) is the projection with the largest difference in average probability, with the German experts estimating its probability to be higher. In addition, the two groups also differ significantly in their average estimates of the impact of the projections on firms ($p < 0.05$, $r = 0.306$). For 17 of the 24 projections, the German experts ($M = 3.17$, $SD = 0.37$) assessed the firm impact as being lower than the experts from the rest of the world did ($M = 3.36$, $SD = 0.30$). Exemplary projections that yielded high differences in impact estimates between the two groups are (P5), (P16), (P20), and (P21). Whereas the German experts estimated lower firm impacts for production workers (P20) and plant managers (P21) working from home, they assessed platform providers as mediators for data sharing (P5) and full transparency of production systems based on digital twins (P16) as being more impactful than the other experts.

4 Summary

The experts project that in the coming decade, we will see a significant increase in the use of production data in the form of digital shadows, which will in turn shape both internal and external processes of manufacturing companies. The experts ascribe a high probability and a high firm impact to the visions of achieving full transparency of production processes via digital twins of production machines, production lines, and plant engineering and operation. This progress in creating comprehensive datasets comprising information on all relevant aspects of production will create vast opportunities, from improving decision-making through AI-based assistance to creating new business models by sharing data between companies and providing newly developed digital services. However, although the experts provided positive assessments for the central vision of Next Generation Manufacturing, their responses also emphasize that there is still considerable uncertainty about how exactly the deployment of digital shadows will impact the production landscape, as shown by the dissent among them for most projections. These differences in the experts' assessments can be partially attributed to their different professional and regional backgrounds. This observation highlights both the importance of using a diverse panel of experts to forecast Next Generation Manufacturing and the need for further research on the differences between the perspectives of various groups of experts. Indeed, the latter is especially important, as the opinions and expectations of relevant stakeholders will have a direct influence on future developments, with significant differences between stakeholder groups potentially leading to tensions or divergent developments in different geographic and economic areas. To conclude, data-based optimization and value creation will be a central part of Next Generation Manufacturing, though the details are still difficult to predict.

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Appendix

Table 1 List of the 24 projections with descriptive statistics of the expert assessments

					Probability of occurrence (in %)			Firm impact
	P#	Projection	Description	N	*IQR*	*M*	*SD*	*M*
Governance	1	Subscription models	In 2030, subscription models for production machines will be the new industry standard, fulfilling an assured performance level based on real-time usage data in return for a periodic payment	35	2.0	57.79	19.22	3.32
	2	Digital services	In 2030, for production machinery and other hardware assets, e.g., tractors, equipment, etc., competition will shift from hardware capabilities and functionality to differentiation by (digital) services, supplementing the traditional transactional business logic with a data-driven business model	35	3.0	65.00	19.85	3.65
	3	Data sharing	In 2030, organizations that share usage and production data with suppliers, customers, and other partners will obtain a competitive advantage over organizations that do not share this data	33	3.0	62.58	21.89	3.55
	4	Central platform	In 2030, one central platform provider will serve as the operating system for the Industrial Internet of Things, enabling them to make use of data by integrating machine manufacturers and complementary service providers and capturing the greatest share of the value created	33	4.0	30.15	18.93	3.09
	5	Data mediator	In 2030, platform orchestrators or dedicated third-party providers will mediate data sharing between all actors involved in a production network	32	4.1	52.34	24.65	3.09
	6	Industrial GDPR	In 2030, industrial data protection regulations (like a special GDPR – General Data Protection Regulation for Business-to-Business) will govern the application of data-based digital services	31	2.5	60.16	22.52	3.52

Organization	7	Autonomous robots	In 2030, collaborative robots that move autonomously on the shop floor and interact directly with humans will have replaced most conventional robots that only interact in protected cells	31	3.5	40.81	25.72	3.06
	8	Hybrid intelligence	In 2030, strategic production decisions will be executed with close interaction between humans and AI-based algorithms (“hybrid intelligence”)	30	3.0	65.13	23.66	3.71
	9	AI-based assistants	In 2030, operative production decisions will no longer lie with people, as they will be made by AI-based decision-making agents	30	3.5	49.68	22.61	3.48
	10	New leadership	In 2030, AI-based decision systems will have changed our current understanding of management completely, increasingly eliminating hierarchies and leadership based on human interactions	30	3.0	34.19	20.25	3.10
	11	Human digital twins	In 2030, a full digital twin of each production worker and all of her/his operations will be available and will become a valuable tool for production planning and optimization by reflecting their workload, their stress, and also their need for training in real time	30	3.8	44.19	23.80	3.13
	12	Employees’ rights	In 2030, adequate anonymization procedures for the protection of employees’ personal rights will have been introduced for firms that collect data on personal performance and work patterns in the form of digital twins of their employees	29	5.0	57.07	26.01	2.93
	13	Workforce reduction	In 2030, AI-based software and robots will have reduced a firm’s workforce significantly	29	2.0	51.55	18.85	3.62
Capabilities	14	Expert knowledge	In 2030, implicit expert knowledge which traditionally could only be gained through experience will increasingly be explicitly preserved in the form of digital models, interactive guides, or instructions and facilitated by technologies like augmented or virtual reality. As a result, this knowledge will also be made available to novices and will eliminate the dependency on experienced production employees	29	3.5	52.07	20.95	3.28
	15	Environmental sustainability	In 2030, environmental sustainability of production will have increased significantly compared to today	29	2.0	67.24	19.14	3.59
	16	Production transparency	In 2030, full transparency based on a complete digital twin of all production machines, lines, and plant engineering and a complete digital twin of their operations will increase production efficiency significantly	29	3.0	65.17	20.82	3.62

(continued)

Table 1 (continued)

	P#	Projection	Description	N	Probability of occurrence (in %)			Firm impact
					IQR	*M*	*SD*	*M*
	17	University degrees	In 2030, the application of biological principles (e.g., cybernetics, biomimicry) of manufacturing will have created a demand for new multidisciplinary university degrees covering engineering, the life sciences, and computer science	29	3.0	50.69	23.48	2.66
Interfaces	18	Implicit interfaces	In 2030, human-machine interaction will have evolved away from explicit interaction, where the human operator has full control of the actions of the production system's entities, toward implicit interaction, where the system automatically adapts to the human operator's behavior by detecting and predicting their actions and modifying these actions accordingly	29	3.0	52.07	17.93	3.07
	19	Open interfaces	In 2030, regulatory requirements will demand open and standardized interfaces for data exchange for all kinds of manufacturing equipment	29	3.6	44.48	21.77	3.17
	20	Production from home	In 2030, production employees will operate their workstation from their home, controlling, for example, remotely operated robots	29	3.0	38.10	24.93	2.83
	21	Plant management from home	In 2030, plant directors will be able to manage multiple factories centrally from their home due to the complete and real-time transparency of all the operations in a digital system	29	4.0	46.03	25.61	2.90
Resilience	22	Decentralization	In 2030, supply chains will have become more decentralized, with production and sourcing moving closer to the end customer to cope better with global crises (e.g., pandemics)	29	2.0	56.55	21.34	3.17
	23	Production costs	In 2030, production costs will have increased substantially due to more regional production and higher inventory levels to cope with global crises (e.g., pandemics)	30	2.5	37.90	20.37	2.94
	24	Production resilience	In 2030, AI-based decision systems will enable greater resilience of production networks in the event of a global crisis (e.g., a pandemic)	29	2.9	40.52	19.88	2.90

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