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Jan Pennekamp

Secure Collaborations for the Industrial Internet of Things

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Secure Collaborations for the Industrial Internet of Things

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Abstract

The Industrial Internet of Things (IIoT) is leading to increasingly-interconnected and networked industrial processes and environments, which, in turn, results in stakeholders gathering vast amounts of information. Although the global sharing of information and *industrial collaborations* in the IIoT promise to enhance productivity, sustainability, and product quality, among other benefits, most information is still commonly encapsulated in local information silos. In addition to interoperability issues, *confidentiality concerns* of involved stakeholders remain the main obstacle to fully realizing these improvements in practice as they largely hinder real-world industrial collaborations today. Therefore, this dissertation addresses this mission-critical research gap. Since existing approaches to privacy-preserving information sharing are not scalable to industry-sized applications in the IIoT, we present solutions that enable *secure* collaborations in the IIoT while providing technical (confidentiality) guarantees to the involved stakeholders. Our research is crucial (i) for demonstrating the potential and added value of (secure) collaborations and (ii) for convincing cautious stakeholders of the usefulness and benefits of technical building blocks, enabling reliable sharing of confidential information, even among direct competitors.

Our *interdisciplinary* research thus focuses on establishing and realizing secure industrial collaborations in the IIoT. In this regard, we study two overarching angles of collaborations in detail. First, we distinguish between collaborations along and across supply chains, with the former type entailing more relaxed confidentiality requirements. Second, whether or not collaborators know each other in advance implies different levels of trust and requires different technical guarantees. We rely on well-established building blocks from *private computing* (i.e., privacy-preserving computation and confidential computing) to reliably realize secure collaborations. We thoroughly evaluate each of our designs, using multiple real-world use cases from production technology, to prove their practical feasibility for the IIoT.

By applying private computing, we are indeed able to secure collaborations that not only scale to industry-sized applications but also allow for use case-specific configurations of confidentiality guarantees. In this dissertation, we use well-established building blocks to assemble novel solutions with technical guarantees for all types of collaborations (along and across supply chains as well as with known or unknown collaborators). Finally, on the basis of our experience with engineers, we have derived a *research methodology* for future use that structures the process of interdisciplinary development and evaluation of secure collaborations in the evolving IIoT.

Overall, given the aforementioned improvements, our research should greatly contribute to convincing even cautious stakeholders to participate in (reliably-secured) industrial collaborations. Our work is an essential first step toward establishing widespread information sharing among stakeholders in the IIoT. We further conclude: (i) collaborations can be reliably secured, and we can even provide technical guarantees while doing so; (ii) building blocks from private computing scale to industrial applications and satisfy the outlined confidentiality needs; (iii) improvements resulting from industrial collaborations are within reach, even when dealing with cautious stakeholders; and (iv) the interdisciplinary development of sophisticated yet appropriate designs for use case-driven secure collaborations can succeed in practice.

Kurzfassung

Das industrielle Internet der Dinge (IIoT) führt zu vernetzten industriellen Prozessen, wodurch viele Informationen gesammelt werden. Obwohl der globale Austausch von Informationen und *industrielle Zusammenarbeit* erhebliche Verbesserungen (wie z.B. Produktivität, Nachhaltigkeit, Produktqualität und weiteres) versprechen, sind die Daten häufig nur lokal zugängig. Neben Interoperabilitätsproblemen behindern heutzutage vor allem *Vertraulichkeitsbedenken* die Etablierung von industrieller Zusammenarbeit. Mit dieser Dissertation adressieren wir diese Bedenken. Da bestehende Konzepte zum sicheren Teilen von Informationen nicht für industrielle Zwecke geeignet sind, stellen wir Lösungen vor, die eine *sichere* Zusammenarbeit im IIoT ermöglichen und gleichzeitig technische Garantien bieten. Unsere Forschung ist von entscheidender Bedeutung, um (i) das Potenzial und den Mehrwert von (sicherer) Zusammenarbeit aufzuzeigen und (ii) reservierte Unternehmen vom Nutzen und den Vorteilen technischer Bausteine zu überzeugen, die einen zuverlässigen Austausch vertraulicher Informationen ermöglichen, selbst zwischen direkten Wettbewerbern.

Unsere *interdisziplinäre* Forschung konzentriert sich daher auf die Etablierung und Realisierung von sicherer industrieller Zusammenarbeit im IIoT. Wir unterscheiden dabei nicht nur zwischen Kooperationen entlang und über Lieferketten hinweg, sondern auch, ob sich die beteiligten Unternehmen im Voraus kennen oder nicht. Diese Dimensionen zeigen verschiedene Vertrauensverhältnisse auf und benötigen somit in der Umsetzung unterschiedlich starke technische Garantien. Wir verwenden dabei bewährte technische Bausteine um vertrauenswürdige industrielle Zusammenarbeiten zuverlässig zu realisieren. Wir evaluieren unsere vorgestellten Entwürfe umfangreich anhand von realen Anwendungsfällen aus dem Bereich der Produktionstechnik, auch um ihren praktischen Nutzen für Unternehmen im IIoT zu belegen.

Der Einsatz der bewährten Bausteine erlaubt uns in der Tat Lösungen zu erstellen, die nicht nur sicher sind, sondern auch für den Einsatz in verschiedenen industriellen Anwendungsszenarien geeignet sind. In dieser Dissertation haben wir etablierte Bausteine kombiniert um neuartige Lösungen mit technischen Garantien für alle Arten von industrieller Zusammenarbeit (entlang und über Lieferketten hinweg sowie mit bekannten oder unbekannten Unternehmen) zu realisieren. Basierend auf unseren Erfahrungen in der Zusammenarbeit mit Ingenieuren haben wir außerdem eine *Methodik für interdisziplinäre Forschung* hergeleitet, die diesen Prozess strukturiert.

Insgesamt sollten unsere Forschungsergebnisse angesichts der zu erwartenden Verbesserungen einen Beitrag leisten, auch zurückhaltende Unternehmen zu überzeugen, sich an (zuverlässig gesicherten) industriellen Kooperationen zu beteiligen. Unsere Arbeit ist somit ein wesentlicher Schritt zur Etablierung von industrieller Zusammenarbeit im IIoT. Außerdem folgern wir aus unseren Ergebnissen: (i) industrielle Kooperationen können zuverlässig abgesichert werden, und wir können dabei sogar technische Garantien bieten, (ii) bestehende Bausteine zum sicheren Informationsaustausch können auch im industriellen Kontext angewendet werden, (iii) Verbesserungen, die sich aus industrieller Zusammenarbeit ergeben, sind somit in Reichweite, selbst wenn man mit skeptischen Unternehmen zu tun hat, und (iv) die interdisziplinäre Entwicklung anspruchsvoller und dennoch geeigneter Designs für anwendungsbezogene sichere Zusammenarbeit kann auch für die praktische Nutzung gelingen.

Acknowledgments

First and foremost, I want to express my gratitude to Andriy, Fabian, and Martin, who got me excited about research as part of their international collaboration during my Bachelor's degree. Without you, I would not be where I am today and I would not even have started this chapter. Moreover, concluding this chapter has only been possible since Prof. Klaus Wehrle and Prof. Florian Kerschbaum served as evaluators of this dissertation. I would like to particularly thank Klaus for allowing me to pursue my own ideas, doing my doctorate part-time, and giving me the freedom to develop myself in many ways and different research domains. Moreover, I am grateful to Florian for the pleasant exchange, despite initially approaching you as a greenhorn, as well as for going out of your way to take such a notable role in my doctoral committee. Lastly, as I would have expected following our previous encounters, Prof. Wil van der Aalst and Prof. Stefan Decker served with the best professional conduct on my committee, which is greatly appreciated. Thank you all!

Second, I am fortunate that throughout my doctoral studies, several gears engaged quite well: (i) Interdisciplinary research in the Cluster of Excellence "Internet of Production" exposed me to many new perspectives, colleagues, and ways of working. (ii) Joint research with (distinguished) students and graduate assistants frequently led to publication, also due to the support of various (interdisciplinary) co-advisors. (iii) Several colleagues (at COMSYS) greatly supported me with my paper writing, especially Roman, Markus, Lennart, Erik, and Martin. Likewise, Joscha provided me with on-point feedback while revising the numerous plots of this dissertation. Unfortunately, naming each and every one would go beyond the scope, but please be sure that I have neither forgotten your contributions nor what I have learned in every project, paper, and cooperation. In this context, I even had the pleasure of coordinating and agreeing on (larger) international research activities and projects. These elements essentially form the basis of this dissertation. (iv) Without the pandemic, my research would not have progressed as it did (a limited social life and the lack of business trips can do wonders…). Still, I had to take a sprint while writing up this dissertation (first as part of our Dagstuhl writing retreat and then in parallel to the daily madness at the office). (v) Last but not least, even though a significant part of this dissertation was created while working from home for over two years, knowing to have a good soul at the office has been a pleasure. Claudia, thank you for having an open ear and for taming the finances and all personnel matters. Combined, these gears and my CV of failures make up my academic journey so far.

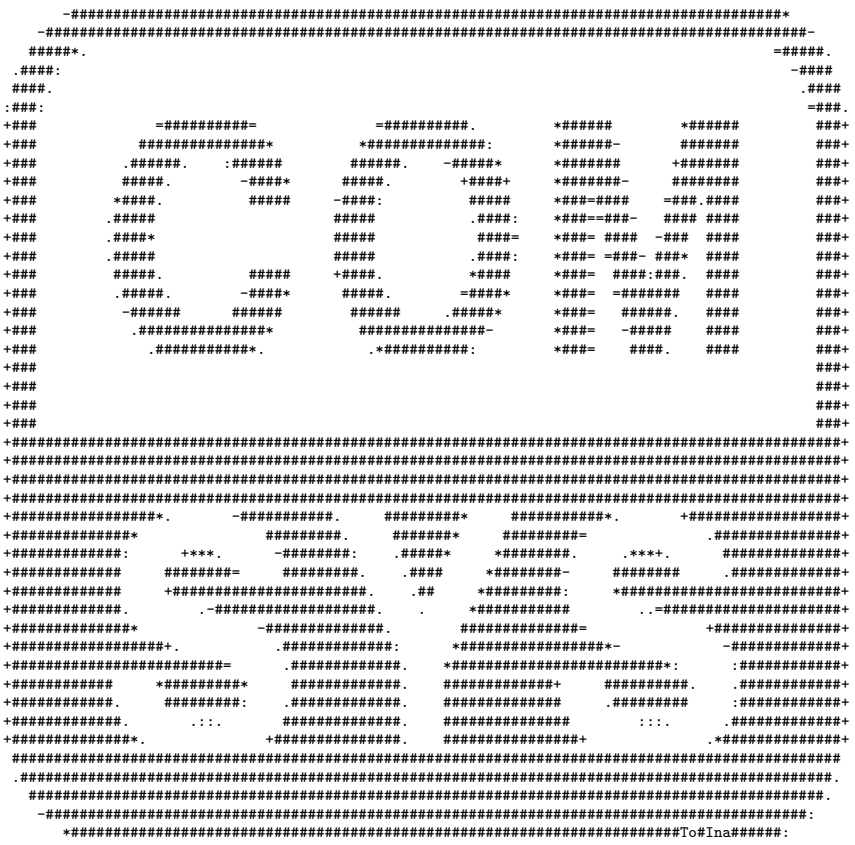
Third, my proofreaders (Eric, Erik, Ike, Ina, Jens, Johannes, Lennart, Markus, Martin, Robert, Roman, Rut, and the language center) might have overlooked some mistakes (just like me). Now, these issues will be retained for eternity; so, thanks!

Fourth, apart from these content-specific matters, I would also like to say thank you for the privilege of traveling together with various colleagues (Martin, Ike, Helge, Roman, Johannes, and Christian), as well as meeting friends and colleagues along these journeys (Philip, Andriy, Asya, Sebastian, Fritz, Florian—twice—, Dominik, Erik, Angelika, Tamer, David, and Lea). Additionally, I would not be the same without the role model function of Martin, Torsten, Jan, Jens, and Roman, as well

as the inventors of the conference call. Then again, I would also like to take this opportunity to thank Alex, Constantin, David and David, Dirk, Eric, Felix, Ike, Ina, Johannes, JT, Kai, Konrad, Lars, Liam, Niklas, Patrick, Philipp, Rainer, René, Salil, Sascha, Stefan, Timo, and Yannik. I believe you know your place in my story.

Fifth, primarily, Moritz and Malte made sure that I had distractions from work through our vacations; but this note also applies to so many others. Moreover, my friends helped me navigate a few challenging times in the past: Here, I would like to mention Marco first and foremost, but also Felix, Moritz, Robert, Roman, and Ina.

Finally, to my friends, brother, and colleagues (i.a., Erik, Erik, Felix, Julius, Malte ⓒ, Simon, and Tim) who are still pursuing their doctorates at this point, go on, and pull through. I looking forward to receiving invitations to attending your defenses down the road! You will be just fine and turn out to be worthy doctorate holders.



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Published Papers

Parts of this dissertation are based on the following peer-reviewed papers that have already been published. All my collaborators are among my co-authors. A detailed attribution of contributions can be found after the list of supervised theses.

List of Publications

[BDJ+22] Philipp Brauner, Manuela Dalibor, Matthias Jarke, Ike Kunze, István Koren, Gerhard Lakemeyer, Martin Liebenberg, Judith Michael, **Jan Pennekamp**, Christoph Quix, Bernhard Rumpe, Wil van der Aalst, Klaus Wehrle, Andreas Wortmann, and Martina Ziefle. A Computer Science Perspective on Digital Transformation in Production. *ACM Transactions on Internet of Things*, 3(2), May 2022.

[BPM+21] Lennart Bader, **Jan Pennekamp**, Roman Matzutt, David Hedderich, Markus Kowalski, Volker Lücken, and Klaus Wehrle. Blockchain-Based Privacy Preservation for Supply Chains Supporting Lightweight Multi-Hop Information Accountability. *Information Processing & Management*, 58(3), May 2021.

[GPL+20] Lars Gleim, **Jan Pennekamp**, Martin Liebenberg, Melanie Buchsbaum, Philipp Niemietz, Simon Knape, Alexander Epple, Simon Storms, Daniel Trauth, Thomas Bergs, Christian Brecher, Stefan Decker, Gerhard Lakemeyer, and Klaus Wehrle. FactDAG: Formalizing Data Interoperability in an Internet of Production. *IEEE Internet of Things Journal*, 7(4):3243–3253, April 2020.

[PAB+24] **Jan Pennekamp**, Fritz Alder, Lennart Bader, Gianluca Scopelliti, Klaus Wehrle, and Jan Tobias Mühlberg. Securing Sensing in Supply Chains: Opportunities, Building Blocks, and Designs. *IEEE Access*, 12:9350–9368, January 2024.

[PAM+20] **Jan Pennekamp**, Fritz Alder, Roman Matzutt, Jan Tobias Mühlberg, Frank Piessens, and Klaus Wehrle. Secure End-to-End Sensing in Supply Chains. In *Proceedings of the 2020 IEEE Conference on Communications and Network Security (CNS '20)*. IEEE, July 2020. Proceedings of the 5th International Workshop on Cyber-Physical Systems Security (CPS-Sec '20).

[PBD+21] **Jan Pennekamp**, Erik Buchholz, Markus Dahlmanns, Ike Kunze, Stefan Braun, Eric Wagner, Matthias Brockmann, Klaus Wehrle, and Martin Henze. Collaboration is not Evil: A Systematic Look at Security Research for Industrial Use. In *Proceedings of the Workshop on Learning from Authoritative Security Experiment Results (LASER '20)*. ACSAC, December 2021.

[PBL+20] **Jan Pennekamp**, Erik Buchholz, Yannik Lockner, Markus Dahlmanns, Tiandong Xi, Marcel Fey, Christian Brecher, Christian Hopmann, and Klaus Wehrle. Privacy-Preserving Production Process Parameter Exchange. In *Proceedings of the 36th Annual Computer Security Applications Conference (ACSAC '20)*, pages 510–525. ACM, December 2020.

[PBM+20] **Jan Pennekamp**, Lennart Bader, Roman Matzutt, Philipp Niemietz, Daniel Trauth, Martin Henze, Thomas Bergs, and Klaus Wehrle. Private Multi-Hop Accountability for Supply Chains. In *Proceedings of the 2020 IEEE International Conference on Communications Workshops (ICC Workshops '20)*. IEEE, June 2020. Proceedings of the 1st Workshop on Blockchain for IoT and Cyber-Physical Systems (BIoTCPS '20).

[PDF+23] **Jan Pennekamp**, Markus Dahlmanns, Frederik Fuhrmann, Timo Heutmann, Alexander Kreppein, Dennis Grunert, Christoph Lange, Robert H. Schmitt, and Klaus Wehrle. Offering Two-Way Privacy for Evolved Purchase Inquiries. *ACM Transactions on Internet Technology*, 23(4), November 2023.

[PDG+19] **Jan Pennekamp**, Markus Dahlmanns, Lars Gleim, Stefan Decker, and Klaus Wehrle. Security Considerations for Collaborations in an Industrial IoT-based Lab of Labs. In *Proceedings of the 3rd IEEE Global Conference on Internet of Things (GCIoT '19)*. IEEE, December 2019.

[PFD+21] **Jan Pennekamp**, Frederik Fuhrmann, Markus Dahlmanns, Timo Heutmann, Alexander Kreppein, Dennis Grunert, Christoph Lange, Robert H. Schmitt, and Klaus Wehrle. Confidential Computing-Induced Privacy Benefits for the Bootstrapping of New Business Relationships. Technical Report RWTH-2021-09499, RWTH Aachen University, November 2021. Blitz Talk at the 2021 Cloud Computing Security Workshop (CCSW '21).

[PGH+19] **Jan Pennekamp**, René Glebke, Martin Henze, Tobias Meisen, Christoph Quix, Rihan Hai, Lars Gleim, Philipp Niemietz, Maximilian Rudack, Simon Knape, Alexander Epple, Daniel Trauth, Uwe Vroomen, Thomas Bergs, Christian Brecher, Andreas Bührig-Polaczek, Matthias Jarke, and Klaus Wehrle. Towards an Infrastructure Enabling the Internet of Production. In *Proceedings of the 2nd IEEE International Conference on Industrial Cyber Physical Systems (ICPS '19)*, pages 31–37. IEEE, May 2019.

[PHS+19] **Jan Pennekamp**, Martin Henze, Simo Schmidt, Philipp Niemietz, Marcel Fey, Daniel Trauth, Thomas Bergs, Christian Brecher, and Klaus Wehrle. Dataflow Challenges in an *Internet* of Production: A Security & Privacy Perspective. In *Proceedings of the ACM Workshop on Cyber-Physical Systems Security & Privacy (CPS-SPC '19)*, pages 27–38. ACM, November 2019.

[PHW21] **Jan Pennekamp**, Martin Henze, and Klaus Wehrle. Unlocking Secure Industrial Collaborations through Privacy-Preserving Computation. *ERCIM News*, 126:24–25, July 2021. *Non-peer-reviewed paper.*

[PLV+23] **Jan Pennekamp**, Johannes Lohmöller, Eduard Vlad, Joscha Loos, Niklas Rodemann, Patrick Sapel, Ina Berenice Fink, Setz Schmitz, Christian Hopmann, Matthias Jarke, Günther Schuh, Klaus Wehrle, and Martin Henze. Designing Secure and Privacy-Preserving Information Systems for Industry Benchmarking. In *Proceedings of the 35th International Conference on Advanced Information Systems Engineering (CAiSE '23)*, pages 489–505. Springer, June 2023.

[PMK+21] **Jan Pennekamp**, Roman Matzutt, Salil S. Kanhere, Jens Hiller, and Klaus Wehrle. The Road to Accountable and Dependable Manufacturing. *Automation*, 2(3):202–219, September 2021.

[PMK+24] **Jan Pennekamp**, Roman Matzutt, Christopher Klinkmüller, Lennart Bader, Martin Serror, Eric Wagner, Sidra Malik, Maria Spiß, Jessica Rahn, Tan Gürpinar, Eduard Vlad, Sander J. J. Leemans, Salil S. Kanhere, Volker Stich, and Klaus Wehrle. An Interdisciplinary Survey on Information Flows in Supply Chains. *ACM Computing Surveys*, 56(2), February 2024.

[PSF+20] **Jan Pennekamp**, Patrick Sapel, Ina Berenice Fink, Simon Wagner, Sebastian Reuter, Christian Hopmann, Klaus Wehrle, and Martin Henze. Revisiting the Privacy Needs of Real-World Applicable Company Benchmarking. In *Proceedings of the 8th Workshop on Encrypted Computing & Applied Homomorphic Cryptography (WAHC '20)*, pages 31–44. HomomorphicEncryption.org, December 2020.

Dissertation Digest

This dissertation has further been summarized as part of a peer-reviewed digest.

[Pen24] **Jan Pennekamp**. Evolving the Industrial Internet of Things: The Advent of Secure Collaborations. In *Proceedings of the 2024 IEEE/IFIP Network Operations and Management Symposium (NOMS '24)*. IEEE, May 2024.

Supervised Theses

Parts of this dissertation are based on the following Bachelor's and Master's theses that were written by students under my supervision. For all theses, I developed the project topic, goals, and fundamental architectural and evaluation design, while my co-advisors provided feedback and domain expertise. The student respectively developed the detailed thesis concept, implementation, and evaluation, as well as the written thesis. All (co-)advisors contributed feedback and reviewed the theses.

List of Supervised Theses

[Bad20] Lennart Bader. Privacy and Transparency in Digital Supply Chains. Advisors: **Jan Pennekamp**, Roman Matzutt, and Philipp Niemietz. Examiners: Klaus Wehrle and Thomas Bergs. Master's Thesis. RWTH Aachen University, February 2020.

[Buc20] Erik Buchholz. Privacy-Preserving Exchange of Process Parameters. Advisors: **Jan Pennekamp** and Yannik Lockner. Examiners: Klaus Wehrle and Christian Hopmann. Master's Thesis. RWTH Aachen University, June 2020.

[Fuh21] Frederik Fuhrmann. Two-way Privacy For Purchase Inquiries in Industry. Advisors: **Jan Pennekamp** and Timo Heutmann. Examiners: Klaus Wehrle and Robert H. Schmitt. Master's Thesis. RWTH Aachen University, January 2021.

[Jes21] Fabian Thorsten Jess. Enhancing Supply Chain Management with Trustworthy and Reliable Sensor Data. Advisors: **Jan Pennekamp**, Lennart Bader, and Fritz Alder. Examiners: Klaus Wehrle and Frank Piessens. Bachelor's Thesis. RWTH Aachen University, August 2021.

[Mic21] Jan-Gustav Michnia. Improving Privacy-Preserving Company Benchmarking with Modern FHE Schemes. Advisors: **Jan Pennekamp**, Niklas Rodemann, and Martin Henze. Examiners: Klaus Wehrle and Günther Schuh. Bachelor's Thesis. RWTH Aachen University, November 2021.

[Siu20] Alexander Stanislaw David Siuda. Web-Based Privacy-Preserving Comparison of KPIs. Advisors: **Jan Pennekamp** and Martin Henze. Examiners: Klaus Wehrle and Elmar Padilla. Bachelor's Thesis. RWTH Aachen University, October 2020.

[Vla22] Eduard Vlad. Applying Trusted Execution for Privacy-Preserving Company Benchmarking. Advisors: Johannes Lohmöller, **Jan Pennekamp**, and Patrick Sapel. Examiners: Klaus Wehrle and Christian Hopmann. Bachelor's Thesis. RWTH Aachen University, September 2022.

[Wag20] Simon Wagner. Privacy-Preserving Company Benchmarking. Advisors: **Jan Pennekamp**, Martin Henze, and Patrick Sapel. Examiners: Klaus Wehrle and Christian Hopmann. Bachelor's Thesis. RWTH Aachen University, September 2020.

Attribution of Contributions

Parts of this dissertation are based on collaborations with students, researchers, and practitioners from industry. The resulting publications form the scientific foundation of this dissertation and were created with the support of the respective co-authors. We now attribute the parts of this dissertation to the respective publications, theses, and authors. We disseminate only parts of the attributed publications. Accordingly, these referenced publications contain additional information, evaluations, and discussions. If not explicitly stated otherwise, in addition to bootstrapping the collaborations with domain experts, the author of this dissertation was responsible for their initial concepts, methodologies, and designs, as well as the final publication.

Background M.H. initially suggested to pursue the research questions of two papers [PGH+19, PHS+19]. J.P. organized and managed the collaborations. J.P. and M.H. jointly developed the outline [PGH+19] and jointly worked on the content and presentation [PHS+19], which is based on discussions with P.N. and S.S. With input from P.N., R.G. contributed the fine blanking use case. M.R. and S.K. prepared the high-pressure die casting and connected job shop use cases, respectively. T.M., R.H., L.G., and C.Q. provided the expertise and presentation on data management. J.P., M.D., and L.G. jointly conducted the work [PDG+19] based on the concept of J.P. Furthermore, J.P. supported L.G. with his paper [GPL+20] by contributing his view on data security. Overall, L.G., J.P., M.L., M.B., P.N., and S.K. jointly worked on the paper. J.P., R.M., and J.H. jointly wrote the paper [PMK+21] following the initiative of J.P. The discussions with S.S.K. greatly supported our work.

Use Cases The use case descriptions are based on information (and visualizations) provided by domain experts. Their input is distributed to the selected applications as follows. P.N. is the fine-blanking expert [PGH+19, PHS+19, PBM+20]. D.H. provided the details of the urban electric vehicle [BPM+21]. While S.K. and T.X. assisted with the connected job shop [GPL+20, PBL+20], T.H., A.K., and D.G. conveyed their knowledge of procurement processes [PDF+23]. P.S. (injection molding) and N.R. (global production networks) supported the company benchmarking descriptions [PLV+23]. Y.L. contributed his injection molding expertise [PBL+20].

Information Processing in Supply Chains Our interdisciplinary survey on information flows in supply chains [PMK+24] is a collaborative effort that greatly exceeds the scope of this thesis. The relevant attribution of contributions for this dissertation is as follows. M.S., J.R., and T.G. drafted the general use cases in supply chains. Together with J.P. and C.K., these use cases were structured and repeatedly revised. In addition, in the context of our sensing paper [PAB+24], J.P. discussed the common sensing applications in supply chains (Section 4.1.2.2) after drafting them with M.S.

Secure and Reliable (End-to-End) Sensing J.P., R.M., and F.A. jointly developed the initial concept [PAM+20]. F.A. and J.T.M. contributed their expertise in trusted computing. J.P., F.A., and J.T.M. jointly worked on the cost evaluation and security discussion. Subsequently, based on a design by L.B. and J.P., F.T.J. implemented a proof of concept for his thesis [Jes21] to link the sensing part of the data processing pipeline with the information-sharing part. J.P., F.A., L.B., and J.T.M. further jointly evolved the initial conceptual design [PAB+24]. While G.S. conducted the evaluation of the sensing part of the data processing pipeline, L.B. provided the results of the blockchain evaluation.

Long-Term Private (Multi-Hop) Information Sharing Jointly, J.P. and R.M. proposed the initial concept [PBM+20]. L.B. significantly evolved this concept during his thesis [Bad20] and evaluated his implementation based on use case data provided by P.N. Aside from that, L.B. further contributed the concept's security discussion as part of his thesis, which was subsequently discussed in detail with J.P. and R.M. before inclusion in the publications [PBM+20, BPM+21]. J.P. discovered and secured (jointly with D.H.) the electric vehicle use case data, which was evaluated and described by L.B. [BPM+21].

Finding New Suppliers with Privacy-Preserving Purchase Inquiries For the thesis of F.F. [Fuh21], T.H. commented on the initial ideas of J.P. and provided the evaluation data. F.F. proposed to also pursue an approach in the direction of cHPI. J.P. and F.F. jointly evolved this initial idea and also came up with HPI. F.F. further implemented and evaluated the designs. For our joint paper [PDF+23], C.L. supported the author of this thesis with his knowledge of data modeling. Additionally, A.K. and D.G. contributed the use case description and helped clarify the steps in today's procurement processes.

Privacy-Preserving Company Benchmarking J.P. and M.H. discussed the initial concept [PSF+20], which S.W. implemented in his thesis [Wag20]. Based on use case data provided by P.S., S.R. conducted the first evaluation of PCB (the initial predecessor of SW-PCB). I.B.F. assisted with the presentation of the design and evaluation. Furthermore, A.S.D.S. implemented the WebAssembly-based client for his thesis [Siu20]. Subsequently, J.G.M. implemented a CONCRETE-based prototype of SW-PCB during his thesis [Mic21], which J.Loo. re-implemented with an updated library version. N.R. contributed another set of use case data. Based on the idea by J.P., J.Loh. and J.P. jointly advised E.V., who implemented HW-PCB, re-implemented SW-PCB in his thesis [Vla22], and evaluated them using both use cases. I.B.F., J.P., J.Loh., M.H., and M.J. discussed the structure of the follow-up paper [PLV+23].

Privacy-Preserving Parameter Exchange J.P. and Y.L. jointly identified the need for research [PBL+20]. J.P. proposed an initial design that was significantly evolved and improved in collaboration with E.B. during his thesis [Buc20]. Based on use case data provided by Y.L., E.B. extensively evaluated his implementation. J.P. and E.B. jointly identified another use case, which E.B. evaluated based on the data provided by T.X. While J.P. and M.D. worked on the line of presentation, E.B. greatly assisted during the writing process.

Appraisal on Secure Industrial Collaborations The outlook of this chapter is influenced by three publications [PHW21, PMK+21, BDJ+22], which J.P. proposed and initiated. Specifically, the strategic research directions are of interest [BDJ+22], which J.P. outlined, drafted in full, and edited afterward based on comments and suggestions by all co-authors. Moreover, the excursus is mainly based on our post-workshop paper [PBD+21]. J.P. initially suggested the presented process cycle, which M.H. later commented on. M.H., M.D., I.K., and E.W. further shared their experience. E.B. reported in detail on experience made during his thesis [Buc20] and our paper submission [PSF+20]. I.K. prepared the discussion on related work after discussions with J.P. Furthermore, S.B. contributed insights on RDM. M.B. sketched a real-world example and commented on our work in light of his domain expertise.

Contents