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Sven-Vegard Buer

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Doctoral thesis

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Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Mechanical and Industrial
Engineering

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Sven-Vegard Buer

Investigating the Relationship between Lean Manufacturing and Industry 4.0

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Thesis for the Degree of Philosophiae Doctor

Trondheim, March 2020

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“Nothing is less productive than to make more efficient what should not be done at all.”

- Peter Drucker (1909–2005)

Summary

Lean manufacturing has for more than two decades been the most prominent methodology for improving the operational performance in manufacturing companies. Originating from the Toyota Production System (TPS) (Ohno, 1988), lean manufacturing is built on the idea of eliminating waste in all forms by focusing on the activities that create value for the customer (Womack and Jones, 1996). It is a low-tech continuous improvement approach that focuses on employee empowerment and the streamlining of manufacturing activities. In parallel with the development of the TPS, computers also slowly started to emerge in manufacturing systems more than 50 years ago, both in processing and in planning and control of the operations (Klingenberg and Antunes Jr., 2017). Recently, the technology-oriented *Industry 4.0* concept is being branded as the next enabler of performance improvement in manufacturing. The Industry 4.0 vision refers to networks of autonomous manufacturing resources that are sensor-equipped and self-configuring, and is enabled by the integration of a large number of different digital technologies (Kagermann et al., 2013). In general, this increased use of digital data and digital technologies is typically referred to as *digitalization*.

Lean manufacturing can work independently of information technology (IT) which by some has been viewed as a source of waste. Lean manufacturing utilizes decentralized control by giving local autonomy to the employees and emphasizes simplicity and transparency, whereas IT focuses on creating a centralized database, and IT systems are rigid, complex, and difficult to change and continuously improve (Åhlström et al., 2016). Although lean manufacturing and Industry 4.0 share the same objective of performance improvement, these underlying contradictory aspects might complicate a concurrent use.

As Industry 4.0 seems destined to overtake lean manufacturing's position as the most prominent approach for performance improvement in manufacturing companies, several relevant issues should be investigated. The theoretical foundation of this thesis is positioned within the operations management research field and investigates the relationship between lean manufacturing and Industry 4.0. We will look further into whether lean manufacturing is an enabler or inhibitor for moving toward Industry 4.0 and if and how these two domains can complement each other. In addition to focusing on lean manufacturing and Industry 4.0, we also take a contingency research approach by investigating in which environments these two domains are appropriate.

The first research activity of this study was to conduct a systematic review of the existing literature on the relationship between lean manufacturing and Industry 4.0. After mapping the current research on this topic and identifying relevant research gaps, we defined three research questions. These are as follows:

1. *What are the implementation patterns of both lean manufacturing and digital technologies across different production environments?*

The first research question aimed at uncovering possible differences in the implementation level of lean manufacturing and that of digital technologies among different production environments. Additionally, we investigated whether there are any significant differences in implementation levels between different company sizes. To answer this research question, we conducted a survey

to investigate the relationships between environmental factors (i.e., production environment and company size) and the implementation levels of both lean manufacturing and digital technologies.

2. *What are the performance implications of a concurrent use of lean manufacturing and digital technologies?*

The second research question sought to investigate the impacts on operational performance from using lean manufacturing and digital technologies. In addition to investigating the main (i.e., individual) effects of lean manufacturing and digital technologies on operational performance, their interaction effect was also investigated. The presence of a positive interaction effect suggests a synergistic effect greater than the main effects combined (Khanchanapong et al., 2014). To address this research question, we used survey data to analyze the relationship between the implementation levels of lean manufacturing and factory digitalization (i.e., the use of digital technologies for internal operations) and the corresponding operational performance.

3. *How can digital technologies be used to support lean manufacturing?*

While most lean manufacturing practices can work independently of IT, part of this research study focused on how the emergence of the digital technologies associated with Industry 4.0 may support and further develop existing lean manufacturing practices. Companies that have already implemented lean manufacturing need guidelines on how to react to the impacts of Industry 4.0 (Meudt et al., 2017) and directions on how emerging technologies can be integrated into existing lean manufacturing systems (Wagner et al., 2017). This research question aimed at investigating the potential of such emerging digital technologies, outlining their possibilities, and presenting different concepts and cases of how they can be integrated with established lean manufacturing practices. To address this research question, we used existing literature, conceptual development, and a case study to highlight examples where digital technologies associated with Industry 4.0 can be or have been used to support existing lean manufacturing practices.

Lean manufacturing and Industry 4.0 have been investigated individually, as well as together. This thesis presents contributions to both theory and practice, which can be summarized as follows:

- *An integrated framework for mapping different production environments.* This framework differs from earlier mapping frameworks in the way that it considers more variables, and the defined values for each variable make it more accessible and easy to use. We suggest that this is, among others, an excellent tool for comparison in multiple case studies where it is expected that environmental factors may influence the results and should be controlled for.
- *New knowledge on the implementation patterns of lean manufacturing practices and of digital technologies across different production environments and company sizes.* These results provide updated findings that can help us understand which parts of lean manufacturing and which digitalization aspects are universal, and which are context-dependent. Knowing the nature of these patterns is important to guide the development of implementation frameworks that take into account the characteristics of different production environments.
- *Providing empirical results showing that both lean manufacturing and factory digitalization individually are related to improved operational performance.* Investigating both simultaneously adds the additional methodological benefit of

controlling for potential confounding effects. The findings also provide support for a complementary effect of lean manufacturing and factory digitalization on operational performance. Our results suggest that the operational performance benefits of implementing either lean manufacturing or digital technologies in isolation are relatively modest. The true operational performance advantage comes when both domains are implemented; in other words, their concurrent use produces a synergistic effect that is larger than the sum of their individual contributions.

- *The presentation of concepts and cases of how digital technologies can support lean manufacturing practices.* This contributes to research by illustrating how these two domains can complement each other. Further, we provide assessments on the benefits and drawbacks of such solutions, how digital technologies can address known limitations in existing lean manufacturing practices, and how it can contribute to improved operational performance.
- *The data-driven process improvement cycle for mapping current digitalization levels, as well as planning and guiding improvement processes.* In addition to clarifying some definitions surrounding the term digitalization, the data-driven process improvement cycle provides a structured method to map existing processes and identify possibilities for further digitalization.

The findings of this thesis also have several implications for practitioners, which can be summarized into the following recommendations:

- Our findings indicate that the implementation level of lean manufacturing is quadratically related to production repetitiveness, which means that the implementation level tends to be lower in production environments with very low or very high repetitiveness. Although implementation level does not equal applicability, these insights should be used by managers to adjust their targets, expectations, and approaches when implementing lean manufacturing instead of forcing through a standardized implementation program.
- The results of this study challenge the opinion that lean manufacturing and IT are incompatible. In fact, the results show that they tend to co-exist and mutually reinforce each other. That the greatest performance benefits are obtained when using lean manufacturing and digital technologies concurrently provides valuable insights when developing roadmaps for production improvement initiatives. With the promise of substantial performance improvements following an Industry 4.0 implementation, there might be the temptation to focus all attention on Industry 4.0 at the expense of lean manufacturing. However, our findings indicate that existing lean manufacturing systems should not be neglected but should rather be used as a basis for deploying new technologies into the manufacturing system.
- The presented concepts and cases of how lean manufacturing and digital technologies can be integrated can be used as inspiration for how to approach the fourth industrial revolution. We recommend using digital technologies to address known problems and limitations in the manufacturing system, rather than digitalizing simply for the sake of it.
- This thesis also presents several frameworks which should be useful for managers. Managers can use the framework for mapping production environments as a starting point for designing appropriate production planning and control solutions, comparing

their operations with other companies, and identifying possible improvement areas. The data-driven process improvement cycle can be used to map the digitalization degree of current processes and provide guidance for how a higher degree of digitalization can be reached.

Overall, this thesis should provide a better understanding and knowledge of the relationship between lean manufacturing and Industry 4.0. This thesis aspires to support those who either manage or study these two domains, individually or in combination.

Sammendrag

Lean produksjon (direkte oversatt *slank produksjon*) har i mer enn to tiår vært den mest fremtredende metoden for å forbedre driftsytelsen i produksjonsbedrifter. Lean produksjon har sitt utspring fra Toyota Production System (TPS) (Ohno, 1988), og er bygget på ideen om å eliminere sløsing i alle former ved å fokusere på aktivitetene som skaper verdi for kunden (Womack and Jones, 1996). Det er en lavteknologisk tilnærming til kontinuerlig forbedring som fokuserer på involvering av de ansatte og strømlinjeforming av produksjonsaktiviteter. I parallell med utviklingen av TPS, begynte også datamaskiner å tas i bruk i produksjonssystemer for over 50 år siden, både for prosessering og for planlegging av styring av produksjon (Klingenberg and Antunes Jr., 2017). Det teknologiorienterte Industri 4.0-konseptet har nylig blitt lansert som den nyeste tilnærmingen for forbedret driftsytelse. Industri 4.0 referer til nettverk av autonome produksjonsressurser som er sensorutstyrte og selvkonfigurerende (Kagermann et al., 2013). Dette er mulig ved å integrere et stort antall forskjellige digitale teknologier. Typisk blir den økte bruken av digitale data og digitale teknologier referert til som *digitalisering*.

Lean produksjon kan fungere uavhengig av informasjonsteknologi (IT), som av noen har blitt sett på som en kilde til sløsing. Lean produksjon benytter desentralisert styring gjennom å gi lokal autonomi til de ansatte, og legger videre vekt på enkelhet og åpenhet. IT, derimot, fokuserer på å opprette en sentralisert database, og IT-systemer er komplekse og vanskelig å endre og kontinuerlig forbedre (Åhlström et al., 2016). Selv om Lean produksjon og Industri 4.0 deler samme mål om forbedret ytelse, kan disse underliggende motstridende aspektene komplisere en samtidig bruk av disse to konseptene.

Ettersom Industri 4.0 ser ut til å overta Lean produksjons posisjon som den mest fremtredende metoden for ytelsesforbedring i produksjonsbedrifter, er det flere relevante spørsmål som bør undersøkes. Det teoretiske fundamentet til denne avhandlingen er posisjonert innenfor Operations Management, og avhandlingen undersøker forholdet mellom Lean produksjon og Industri 4.0. Vi vil se nærmere på hvorvidt Lean produksjon støtter eller hindrer implementeringen av Industri 4.0, og hvorvidt disse to konseptene kan utfylle hverandre. I tillegg til å fokusere på Lean produksjon og Industri 4.0, undersøker vi også i hvilke kontekster implementeringen av de to konseptene er hensiktsmessig.

Den første forskningsaktiviteten i denne studien var en systematisk gjennomgang av eksisterende litteratur som undersøker forholdet mellom Lean produksjon og Industri 4.0. Etter å ha kartlagt eksisterende forskning innenfor dette temaet og identifisert relevante forskningsgap, ble tre forskningsspørsmål definert. Disse er som følger:

1. *Hva er implementeringsmønstrene for både Lean produksjon og digitale teknologier i forskjellige produksjonsmiljøer?*

Det første forskningsspørsmålet tok sikte på å avdekke forskjeller i implementeringsnivå for Lean produksjon og digitale teknologier mellom forskjellige produksjonsmiljøer. I tillegg undersøkte vi om det var vesentlige forskjeller i implementeringsnivå mellom bedrifter av ulik størrelse. For å besvare dette forskningsspørsmålet gjennomførte vi en spørreundersøkelse for å undersøke forholdet mellom to kontekstuelle faktorer (produksjonsmiljø og bedriftsstørrelse) og implementeringsnivåene for både Lean produksjon og digitale teknologier.

2. *Hva er ytelseskonsekvensene av en samtidig bruk av Lean produksjon og digitale teknologier?*

Det andre forskningsspørsmålet undersøkte hvilke effekter Lean produksjon og digitale teknologier har på driftsytelse. I tillegg til å undersøke de individuelle effektene av Lean produksjon og digitale teknologier, undersøkte vi også deres interaksjonseffekt. En signifikant interaksjonseffekt antyder en synergistisk effekt som er større enn kombinasjonen av de individuelle effektene (Khanchanapong et al., 2014). For å besvare dette forskningsspørsmålet brukte vi data fra spørreundersøkelsen til å analysere forholdet mellom bedriftens ytelse og bruken av Lean produksjon og digitale teknologier i produksjonen.

3. *Hvordan kan digitale teknologier brukes til å støtte Lean produksjon?*

Mens de fleste verktøyene innenfor Lean produksjon kan fungere uten bruk av IT, fokuserte deler av denne studien på hvordan digitale teknologier assosiert med Industri 4.0 kan støtte og videreutvikle eksisterende verktøy fra Lean produksjon. Bedrifter som allerede har implementert Lean produksjon trenger retningslinjer for hvordan de skal møte Industri 4.0 (Meudt et al., 2017) og for hvordan nye teknologier kan integreres i eksisterende Lean produksjonssystemer (Wagner et al., 2017). Dette forskningsspørsmålet tok sikte på å undersøke potensialet til nye, digitale teknologier, skissere deres potensial og presentere forskjellige konsepter og eksempler på hvordan de kan integreres med etablerte verktøy fra Lean produksjon. For å besvare dette forskningsspørsmålet brukte vi eksisterende litteratur, konseptutvikling og en case-studie for å presentere eksempler der digitale teknologier assosiert med Industri 4.0 kan bli eller har blitt brukt for å støtte eksisterende verktøy fra Lean produksjon.

Denne avhandlingen har undersøkt Lean produksjon og Industri 4.0 både individuelt og i kombinasjon. Avhandlingen presenterer bidrag både til teori og praksis, som kan oppsummeres som følger:

- *Et rammeverk for kartlegging av forskjellige produksjonsmiljøer.* Dette rammeverket skiller seg fra tidligere kartleggingsrammeverk ved at det vurderer flere variabler, og de definerte alternativene for hver variabel gjør rammeverket enklere i bruk. Vi mener dette kan være et utmerket verktøy blant annet for sammenligning av forskjellige bedrifter i casestudier hvor det er forventet at kontekstuelle faktorer kan påvirke resultatene og bør kontrolleres.
- *Ny kunnskap vedrørende implementeringsmønstrene til Lean produksjon og digitale teknologier på tvers av forskjellige produksjonsmiljøer og bedriftsstørrelser.* Disse resultatene presenterer oppdaterte funn som kan bidra til forståelsen av hvilke deler av Lean produksjon og hvilke aspekter av digitalisering som er universell, og hvilke som er kontekstavhengig. Å kjenne til disse implementeringsmønstrene er viktig for å støtte utviklingen av implementeringsretningslinjer som tar hensyn til karakteristikkene i forskjellige produksjonsmiljø.
- *Empiriske resultater som viser at både Lean produksjon og digitalisering individuelt har en positiv effekt på driftsytelse.* Ved å undersøke begge samtidig, oppnår man også den metodologiske fordelen av å kontrollere for eventuelle konfunderende effekter. Resultatene indikerer også at Lean produksjon og digitalisering sammen har en komplementær effekt på driftsytelse. Disse resultatene antyder at ytelsesfordelene ved å implementere enten Lean produksjon eller digitalisering isolert sett er relativt beskjedne.

De virkelige fordelene kommer først når begge implementeres, med andre ord, samtidig bruk gir en synergistisk effekt som er større enn summen av deres individuelle bidrag.

- *Presentasjon av konsepter og eksempler for hvordan digitale teknologier kan støtte Lean produksjon.* Dette bidrar til forskning ved å illustrere hvordan disse to konseptene kan utfylle hverandre. Videre vurderer vi fordeler og ulemper med de presenterte løsningene, hvordan digitale teknologier kan håndtere kjente begrensinger i Lean produksjon og hvordan det kan bidra til forbedret driftsytelse.
- *Presentasjon av den datadrevne prosessforbedringssyklusen for kartlegging av nåværende digitaliseringsnivåer og veiledning for videre prosessforbedring.* I tillegg til å avklare enkelte definisjoner rundt begrepet digitalisering, foreslår den datadrevne prosessforbedringssyklusen en strukturert metode for å kartlegge eksisterende prosesser og identifisere muligheter for videre digitalisering.

Funnene i denne studien har også en rekke anvendelsesområder for praktikere som kan oppsummeres i følgende anbefalinger:

- Våre funn indikerer at implementeringsnivået for Lean produksjon er kvadratisk relatert til graden av repetivitet i produksjonsprosessen (dvs. hvor ofte identiske produkter blir produsert). Dette betyr at implementeringsnivået typisk er lavere i produksjonsmiljøer med veldig lav eller veldig høy repetivitet. Selv om implementeringsnivå ikke nødvendigvis er det samme som anvendbarhet, kan disse resultatene bli brukt av ledere for å justere sine mål, forventninger og tilnærminger når de implementerer Lean produksjon istedenfor å prøve å tvinge gjennom et standardisert implementeringsprogram.
- Resultatene fra denne studien setter spørsmålstegn ved den typiske oppfatningen av Lean produksjon og IT som inkompatible. Denne studien viser derimot at de har en tendens til å sameksistere og gjensidige styrke hverandre. At de største ytelsesfordelene oppnås når man bruker Lean produksjon og digitale teknologier samtidig, gir verdifull innsikt når man utvikler planer for produksjonsforbedring. Med lovnadene om betydelige ytelsesforbedringer som følge av en implementering av Industri 4.0, kan det være fristende å fokusere all oppmerksomhet på Industri 4.0 på bekostning av Lean produksjon. Disse funnene indikerer imidlertid at eksisterende Lean produksjonssystemer ikke bør ignoreres, men heller bli brukt som et grunnlag for implementeringen av nye teknologier.
- De presenterte konseptene og eksemplene for hvordan Lean produksjon og digitale teknologier kan integreres, kan brukes som inspirasjon for hvordan man bør tilnærme seg den fjerde industrielle revolusjonen. Vi anbefaler å bruke digitale teknologier for å håndtere kjente problemer og begrensninger i produksjonssystemet, istedenfor å digitalisere kun for å digitalisere.
- Avhandlingen presenterer også flere rammeverk som bør være nyttig for ledere. Ledere kan bruke rammeverket for kartlegging av produksjonsmiljøer som et utgangspunkt for å designe passende løsninger for produksjonsplanlegging- og styring, sammenligne seg selv med andre bedrifter og identifisere mulige forbedringsområder. Den datadrevne forbedringssyklusen kan brukes for å kartlegge digitaliseringsgraden av eksisterende prosesser og gi veiledning for hvordan en høyere grad av digitalisering kan oppnås.

Samlet sett bør denne avhandlingen bidra til en bedre forståelse av og mer kunnskap om forholdet mellom Lean produksjon og Industri 4.0. Denne avhandlingen tar sikte på å støtte de som jobber med eller studerer disse to konseptene, individuelt eller kombinert.

Acknowledgements

It goes without saying that this PhD thesis has been completed with a great deal of help provided in the form of ideas and feedback from my colleagues, as well as a great deal of support from my friends and family. I would like to dedicate this section to *everyone* who has supported me over the last three years.

First, I would like to express my gratitude to my supervisors who have guided me through this sometimes bewildering journey toward the submission of this PhD thesis. First, I want to sincerely thank my main supervisor, Jan Ola Strandhagen, for giving me the opportunity to pursue this PhD degree. He has given me the amount of academic freedom that one could only dream of, enabling me to delve into a research topic of my personal interest. At the same time, he has also kept a keen eye on my research to ensure that it has been moving in the right direction.

Luckily, I also had two co-supervisors whom I could seek additional advice from. Marco Semini has been my co-supervisor at NTNU. Thank you for giving me great academic support, especially related to statistical analysis. Felix T.S. Chan has been my co-supervisor in Hong Kong. His knowledge and experience have been very helpful throughout the last three years. Thank you for hosting me on my two visits to Hong Kong Polytechnic University. These visits surely have been an experience of a lifetime. Thanks also go out to Amy, Shuai, and Keith at Hong Kong Polytechnic University for being wonderful hosts and providing fruitful feedback on my work.

Erlend Alfnes, who has been my “informal” supervisor, also deserves my deepest gratitude. He has probably been the one person, except me, who has been most interested in the research work presented in this thesis. Erlend has always been available to read paper drafts and has always had valuable comments to improve my work.

Thanks also go to representatives from the numerous industrial partners I have been fortunate to work with. Each one of you deserves recognition for contributing to ensure that the research presented in this thesis has been completed. This includes all the respondents who shared their time and responded to the survey that part of this research is based on. A special thanks to Daryl Powell, Elisabeth Haukeland-Parker, Jonas Eriksson, and Stian Johansen at Kongsberg Maritime Subsea for showcasing their digital lean manufacturing projects. And extra thanks to Daryl for sharing his interesting thoughts on lean manufacturing.

Luckily, I did not have to undertake this PhD journey alone, and my fellow PhD students have also been a great support. Thanks to all my current and former PhD colleagues. Their support ranged from exchanging feedback around the coffee machine and in PhD seminars to being travel companions to conferences across the world. Special thanks go to Jo Wessel Strandhagen and Giuseppe Fragapane who co-authored some of the papers included in this thesis. I would also like to express my gratitude to my former colleague Kasper Kiil for sharing his insights into the academic skills and techniques needed to be a successful PhD student.

Last, but certainly not least, I would like to express my gratitude to my parents Liv Karin and Sven-Otto, as well as my sisters Caroline and Silje. As my years as a student draw to a close, your continued support has been essential for me being where I am today.

Trondheim, October 2019
Sven-Vegard Buer

Abbreviations

AI	Artificial intelligence
AMT	Advanced manufacturing technology
ANOVA	Analysis of variance
AR	Augmented reality
ATO	Assemble-to-order
AVE	Average variance extracted
BOM	Bill of material
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
CEO	Chief executive officer
CIM	Computer-integrated manufacturing
COBACABANA	Control of balance by card-based navigation
CODP	Customer order decoupling point
CONWIP	Constant work in process
CPS	Cyber-physical systems
CR	Composite reliability
CTO	Chief technology officer
DMAIC	Define – Measure – Analyze – Improve – Control
ERP	Enterprise resource planning
ETO	Engineer-to-order
FDM	Fused deposition modeling
HSE	Health, safety, and environment
ILP	Internal lean practice
IMRaD	Introduction, methods, results, and discussion
IMVP	International Motor Vehicle Program
IoS	Internet of Services
IoT	Internet of Things
IT	Information technology
JIT	Just-in-time
KMS	Kongsberg Maritime Subsea
KPI	Key performance indicator
LE	Large enterprise
MES	Manufacturing execution system
MRP	Material requirements planning
MRP II	Manufacturing resources planning
MTO	Make-to-order
MTS	Make-to-stock
NSD	Norwegian Centre for Research Data
PDCA	Plan – Do – Check – Act
POLCA	Paired-cell overlapping loops of cards with authorization
PPC	Production planning and control
QR	Quick response
RFID	Radio-frequency identification
RQ	Research question
SD	Standard deviation
SME	Small and medium-sized enterprise

SMED	Single minute exchange of die
SPC	Statistical process control
TPM	Total productive maintenance
TPS	Toyota Production System
VR	Virtual reality
VSM	Value stream mapping
WIP	Work in process

List of Appended Papers and Declaration of Authorship

Paper	**Title**	**Declaration of authorship**
1	Buer, S.V., Strandhagen, J.O. & Chan, F.T.S. (2018), "The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924-2940.	Buer conceptualized the paper and conducted the literature review. Buer wrote the paper with feedback from Strandhagen and Chan.
2	Buer, S.V., Strandhagen, J.W., Strandhagen, J.O. & Alfnes, E. (2018), "Strategic Fit of Planning Environments: Towards an Integrated Framework", *Lecture Notes in Business Information Processing*, Vol. 262, pp. 77-92.	Buer conceptualized the paper and created the framework with input from all co-authors. Buer and J.W. Strandhagen collected the data from the cases. Buer wrote the paper together with J.W. Strandhagen, with input from J.O. Strandhagen and Alfnes.
3	Buer, S.V., Alfnes, E., Semini, M. & Strandhagen, J.O. (2019), "New insights on the relationship between lean manufacturing practices and type of production environment", under review at *Production Planning & Control.*	Buer conceptualized the paper and collected the data with assistance from Strandhagen. Buer analyzed the data with input from Semini. Buer wrote the paper with feedback from Semini and Alfnes.
4	Buer, S.V., Strandhagen, J. W., Semini, M. & Strandhagen, J.O. (2019), "The digitalization of manufacturing: investigating the impact of production environment and company size", under review at *Journal of Manufacturing Technology Management*.	Buer conceptualized the paper and collected the data with assistance from J.O. Strandhagen. Buer analyzed the data with input from Semini. Buer and J.W. Strandhagen wrote the paper with feedback from Semini.
5	Buer, S.V., Semini, M., Strandhagen, J.O. & Sgarbossa, F. (2019), "The complementary effect of lean manufacturing and digitalisation on operational performance: results from a survey of Norwegian companies", under review at *International Journal of Production Research.*	Buer conceptualized the paper and collected the data with assistance from Strandhagen. Buer analyzed the data with input from Semini. Buer wrote the paper with feedback from Semini, Strandhagen and Sgarbossa.
6	Buer, S.V., Fragapane, G.I. & Strandhagen, J.O. (2018), "The Data-Driven Process Improvement Cycle: Using Digitalization for Continuous Improvement", *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 1035-1040.	Buer conceptualized the paper and created the framework together with Fragapane. Buer and Fragapane wrote the paper together with feedback from Strandhagen.

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Introduction 1

Lean manufacturing has for more than two decades been the most prominent methodology for improving the operational performance in manufacturing companies. Originating from the Toyota Production System (TPS) (Ohno, 1988), lean manufacturing is built on the idea of eliminating waste in all forms by focusing on the activities that create value for the customer (Womack and Jones, 1996). It is a low-tech continuous improvement approach that focuses on employee empowerment and the streamlining of manufacturing activities. In parallel with the development of the TPS, computers also slowly started to emerge in manufacturing systems more than 50 years ago, both in processing and in planning and control of the operations (Klingenberg and Antunes Jr., 2017). Recently, the technology-oriented *Industry 4.0* concept is being branded as the next enabler of performance improvement in manufacturing. The Industry 4.0 vision refers to networks of autonomous manufacturing resources that are sensor-equipped and self-configuring, and is enabled by the integration of a large number of different digital technologies (Kagermann et al., 2013). In general, this increased use of digital data and digital technologies is typically referred to as *digitalization*.

Lean manufacturing, on the other hand, can work independently of information technology (IT), which by some has been viewed as a source of waste. Lean manufacturing utilizes decentralized control by giving local autonomy to the employees. Most of the information flow in a lean manufacturing system has traditionally been analog, for instance, through physical Kanban cards and whiteboards positioned throughout the shop floor. Lean manufacturing emphasizes simplicity and transparency, and any problems should be handled immediately, preferably by taking care of the root cause of the problem. In contrast, IT focuses on creating a centralized database and “a single version of the truth,” which creates a disconnect between the reality on the shop floor and the abstract information generated by the IT system. The advanced algorithms found in the IT systems can reduce the perceived simplicity of a process and reduce the transparency of decision-making. This increased complexity and reduced transparency can create distance between the decision-maker and the decision-making process. Furthermore, IT systems are rigid, complex, and difficult to change and continuously improve, thus encouraging workarounds instead of handling the root cause of problems (Åhlström et al., 2016). Although lean manufacturing and Industry 4.0 share the same objective of performance improvement, these underlying contradictory aspects might complicate a concurrent use.

As Industry 4.0 seems destined to overtake lean manufacturing’s position as the most prominent approach for performance improvement in manufacturing companies, several relevant issues should be investigated. First, we have observed that some companies have recently terminated their lean manufacturing program and, in its place, are pursuing opportunities enabled by the newest surge of technological developments. This could indicate that managers see Industry 4.0 as a replacement for lean manufacturing, rather than a complementary approach. Does this suggest that the smart factory prophesied in the Industry 4.0 vision will render lean manufacturing obsolete and no longer a relevant improvement approach for manufacturing companies?

On the other hand, others advocate that technology can be integrated into a lean manufacturing system as long as it supports lean principles and adds value to the process. The introduction of cyber-physical systems (CPS) and the Internet of Things (IoT), key components of Industry 4.0, enable distributed computing and autonomy not typically found in traditional centralized IT systems. Does this mean that Industry 4.0 should be seen as a complementary approach which can support and address limitations in existing lean manufacturing systems?

In contrast with lean manufacturing, which is a proven approach with demonstrated benefits, Industry 4.0 is, for now, mostly a vision for the future of manufacturing. Could it be that Industry 4.0 is merely a management fad, supported by large vendors aiming to sell new hardware and software solutions, and should simply be overlooked?

These are just some of the crucial issues we expect that the industry will have to handle in the coming years and, as such, deserve further research. This thesis investigates the relationship between lean manufacturing and Industry 4.0. We will look further into whether lean manufacturing is an enabler or inhibitor for moving toward Industry 4.0 and if and how these two domains can complement each other.

1.1 Background

The current competitive environment of manufacturing is characterized by, among other things, increasing global competition, shorter product life cycles and increasing individualization of products. This puts pressure both on manufacturing companies' flexibility as well as their resource efficiency to meet customer demand and stay competitive (Lasi et al., 2014). To meet these challenges, companies are forced to continuously innovate and improve their operations management strategies and processes.

Manufacturing companies have throughout the last century adopted numerous methodologies to improve the management of their operations. Out of these, lean manufacturing has arguably been the most prominent (Holweg, 2007; Found and Bicheno, 2016). Lean manufacturing supports manufacturing companies in their efforts to improve in many areas, including reduced production cost, improved quality (Bhamu and Sangwan, 2014), improved responsiveness by reducing lead times (Chauhan and Singh, 2012), and increased flexibility (James-Moore and Gibbons, 1997). Lean manufacturing has in the last decades gained popularity worldwide. Numerous accounts of successful lean manufacturing implementations are reported in both media and academic literature, highlighting how organizations successfully have transformed and streamlined their business operations to achieve performance gains. Being viewed as a source of competitive advantage, an increasing number of companies look toward how they can apply lean manufacturing in their operations. According to a survey released in 2007, almost 70% of American manufacturing plants have implemented some form of lean manufacturing project (Pay, 2008). More recently, a survey from Germany reports that over 90% of the surveyed manufacturing companies claim to have initiated a lean manufacturing initiative (Glass et al., 2016).

However, even if lean manufacturing has helped numerous companies reduce waste and thereby improve in several performance dimensions, many companies still struggle to successfully transform into a lean company (Jadhav et al., 2014). The less successful implementations are less frequently reported in the literature but are seemingly more common (Marodin and Saurin, 2015; Netland, 2016). This often seems to be a result of an inaccurate understanding of lean manufacturing by both management and employees in an organization (Bhamu and Sangwan, 2014). A common mistake is failing to consider the strategic fit of lean manufacturing tools and consequently trying to implement them in environments where they are not applicable (Azadegan et al., 2013). Others might experience that the basic methods of lean manufacturing are not sufficient and, hence, do not meet the company's operational requirements (Kolberg and Zühlke, 2015). Additionally, even though companies seemingly succeed in their initial implementation phase, many find it difficult to sustain the initial momentum of their lean manufacturing project (Netland, 2016). These are just some of the commonly cited challenges with lean manufacturing systems. Thus, there is a need to develop methods for achieving a larger proportion of successful and sustainable lean manufacturing implementations. One approach proposed to address these challenges is to investigate the solutions offered by IT (Pinho and Mendes, 2017).

The rapid technological advances and increased affordability of IT systems, including both hardware and software solutions, accelerate the transition toward a proposed fourth industrial revolution, commonly known as Industry 4.0. Starting out as a German government program, Industry 4.0 represents a collection of various digital technologies which can promote a strategic innovation of the manufacturing industry (Kang et al., 2016). It enables numerous new opportunities for businesses, such as data-driven business models, innovative products, new value chains with an increased level of communication between suppliers and customers, big data analytics to enable self-optimizing resources, and autonomous and flexible machines. Industry 4.0 has gained significant popularity in both academia and in the industrial sector; companies worldwide are investing considerable sums into investigating how they can benefit from this emerging technology-based manufacturing paradigm. Numerous government programs have been established focusing on the digitalization of industry (European Commission, 2017; Liao et al., 2017), and digitalization was also pointed out as one of three main focus areas in the Norwegian government's most recent Industrial Policy (Norwegian Ministry of Trade, Industry and Fisheries, 2017).

In contrast to lean manufacturing, which is a proven approach with demonstrated benefits, we find few examples of full-scale Industry 4.0 implementations. While reports from vendors and consultancy firms outline the numerous possibilities of digital technologies, most manufacturing companies are still in the early stages regarding the implementation of such technologies, and there is still a large potential for future development (Bley et al., 2016; Van den Bossche et al., 2016; Moeuf et al., 2018). This also seems to be the case for Norwegian manufacturing companies (Eleftheriadis and Myklebust, 2017; Torvatn et al., 2019).

All in all, Industry 4.0 is seen as the future of manufacturing and is presented as a concept that manufacturers need to embrace to stay competitive. In that sense, it resembles how lean manufacturing was advertised in the previous decades. This thesis will further investigate the relationship between these two domains.

1.2 Research motivation

The origins of lean manufacturing can be traced back to 1948 (Holweg, 2007), and lean manufacturing in its purest form works completely independent of any kind of IT. The opinion that IT and lean manufacturing are incompatible has been common in both academia and industry for a long time (Pinho and Mendes, 2017). This notion can be traced back to the reflections by Sugimori et al. (1977), who claimed that using computerized systems for material planning increases cost, reduces transparency, and leads to overproduction of goods. As indicated at the beginning of this chapter, advocates of the proposition that IT and lean manufacturing are incompatible typically highlight several underlying contradictions between the domains. While these contradictions might complicate a concurrent use, research has shown that IT can be integrated into lean manufacturing systems if it supports lean principles and adds value to the process. Recently, there has been an increased research effort into how lean manufacturing and IT may cooperate to achieve better performance (Riezebos and Klingenberg, 2009; Powell, 2013; Pinho and Mendes, 2017). Evidence from industry also show that companies are able to build hybrid solutions, where they are able to take advantage of both lean manufacturing and IT solutions, such as enterprise resource planning (ERP) systems (Riezebos et al., 2009), radio-frequency identification (RFID) (Brintrup et al., 2010), or a manufacturing execution system (MES) (Cottyn et al., 2011).

Despite the recent studies investigating the interaction between IT and lean manufacturing, it has been pointed out that there is still a lack of propositions and theory clarifying the relationship between IT and lean manufacturing (Pinho and Mendes, 2017). Especially regarding the newest surge of technology developments associated with Industry 4.0, there is a lack of theory surrounding how this transformation will affect lean manufacturing.

For most manufacturing companies, performance benefits are the main motivation behind exploring improvement programs or investing in new technologies, whether they seek improvements in cost, speed, quality, flexibility, dependability, or other dimensions. The specific performance impact the integration of lean manufacturing and Industry 4.0 will have remains largely unknown (Buer et al., 2018b). While there are previous studies investigating the performance impact of lean manufacturing (e.g., Mackelprang and Nair, 2010) or Industry 4.0 (e.g., Dalenogare et al., 2018) in isolation, a concurrent use of the two domains might result in an enhancing (or synergistic) relationship, in which one resource magnifies the impact of another resource, or a suppressing relationship, in which one resource diminishes the impact of another (Jeffers et al., 2008). Studies investigating both domains simultaneously will thus provide further insights into how these two domains together impact performance, providing valuable contributions to both theory and practice.

In addition to studying the performance implications of improvement initiatives, such as lean manufacturing or Industry 4.0 in general, there is an increasing trend in operations management research to investigate under which contextual conditions best practices are effective (Sousa and Voss, 2008). Originating from the automotive industry, lean manufacturing has its roots in typical repetitive production systems, and the literature has reported significantly more implementations in these environments (Slomp et al., 2009). However, lean manufacturing is spreading to other industries, and today, lean manufacturing practices can be observed in every industry. Thus, the universality of lean manufacturing is a frequently revisited topic. While there have been a few studies investigating the diffusion of lean manufacturing across different production environments (e.g., White and Prybutok, 2001; Shah and Ward, 2003; Olhager and Prajogo, 2012), common for these is that they treat production environments as a variable with only two categories. To gain further insights into the implementation pattern of lean manufacturing, researchers have proposed to investigate this issue with a more detailed typology of different production environments (Portioli-Staudacher and Tantardini, 2012). Similarly, for Industry 4.0, the actual universality of Industry 4.0 remains unclear (Sommer, 2015; Strandhagen et al., 2017). There are few examples of Industry 4.0 applications in non-repetitive production environments (Zennaro et al., 2019), and earlier research has proposed that Industry 4.0 is more applicable in repetitive production environments because of their lower complexity and higher degree of standardization and automation (Strandhagen et al., 2017). Other researchers have questioned whether Industry 4.0, because of the large investment needed, is solely for large enterprises (Sommer, 2015; Rüttimann and Stöckli, 2016).

1.3 Research objectives and questions

Motivated by the challenges and research problem outlined above, this research has focused on investigating the relationship between lean manufacturing and Industry 4.0. While there are numerous unanswered questions and unexplored areas regarding this relationship, this thesis mainly investigates the areas related to *where these two domains are applicable, what the performance impacts are, and how they can be combined in practice.* The objective of this PhD research is thus to provide a better understanding and knowledge of:

- the implementation patterns of lean manufacturing and of digital technologies across different production environments,
- the performance impact of concurrently using lean manufacturing practices and digital technologies, and
- areas where a concurrent application of lean manufacturing and digital technologies can be beneficial.

Similarly, research questions were defined to guide the research process. These are as follows:

RQ1: *What are the implementation patterns of both lean manufacturing and digital technologies across different production environments?*

The first research question aims at uncovering possible differences in the implementation level of lean manufacturing and of digital technologies among a variety of production environments. Additionally, we investigate whether there are any significant differences in implementation levels between different company sizes. The answer to this research question will contribute to the contingency research of both lean manufacturing and digital technologies and highlight their applicability across different production environments and company sizes.

RQ2: *What are the performance implications of a concurrent use of lean manufacturing and digital technologies?*

The second research question aims to investigate the impacts on operational performance from using lean manufacturing and digital technologies. In addition to investigating the main (i.e., individual) effects of both lean manufacturing and digital technologies on operational performance, their interaction effect will also be investigated. The presence of a positive interaction effect suggests a synergistic effect greater than the main effects combined (Khanchanapong et al., 2014). The findings from this research question should provide insights into whether these two domains can create a competitive advantage for manufacturing companies.

RQ3: *How can digital technologies be used to support lean manufacturing?*

While most lean manufacturing practices can work independently of IT, part of this research study focuses on how the emergence of the digital technologies associated with Industry 4.0 may support and further develop existing lean manufacturing practices. Companies that have already implemented lean manufacturing need guidelines on how to react to the impacts of Industry 4.0 (Meudt et al., 2017) and directions on how emerging technologies can be integrated into existing lean manufacturing systems (Wagner et al., 2017). To answer this research question, we will investigate the potential of such emerging digital technologies, outline their possibilities, and present different concepts and cases of how they can integrate with established lean manufacturing practices.

1.4 Research scope

This section will briefly summarize the scope of this study. This research study lies within the operations management research area and studies the relationship between Industry 4.0 and lean manufacturing. However, a complete discussion of the domains introduced so far is a task too extensive for this project. Thus, further scoping of the domains is needed.

Regarding lean manufacturing, this thesis will mainly focus on the internal aspects of lean manufacturing, known as internal lean practices (ILPs) (Li et al., 2005; Shah and Ward, 2007). Supplier-related and customer-related practices of lean manufacturing are thus outside of the scope of this study. It is assumed that these practices are mainly concerned with supply chain and market performance improvement, rather than operational performance improvement (as previously indicated by Prajogo et al., 2016).

Industry 4.0 is a general term, encompassing an increasing number of different technologies. While it is challenging to scope a "moving target" such as Industry 4.0, this thesis will mainly focus on the part of Industry 4.0 we refer to as *digitalization of production*. In many ways, digitalization is a broader term than Industry 4.0 since it has impacted and will continue to impact the whole society for years. In the widest sense, digitalization of production can be defined as "the use of digital data and technology to automate data handling and optimize processes" (Buer et al., 2018a, p. 1036). It is especially related to autonomous data collection and analysis, as well as interconnectivity between products, processes, and people (Buer et al., 2018b; Sjøbakk, 2018). While Industry 4.0 can be described as a vision of how manufacturing will be done in the future, digitalization is seen as a key enabler of getting there (Pfohl et al., 2017). The fact that there are few available cases of full-scale Industry 4.0 implementations to date is one of the factors influencing the choice to focus on digitalization through the use of digital technologies. Furthermore, examples of aspects we do not explicitly discuss in this thesis are concerns related to cybersecurity and data quality, as these are research streams of their own.

Regarding environmental factors (also known as contextual factors), this study mainly focuses on two factors: production environment and company size. While company size is a simple measure based on turnover and number of employees, the production environment is a more comprehensive measure, influenced by a number of sub-factors related to the product, market, and manufacturing process. However, there are other environmental factors that are not considered in this study. National and organizational cultures are examples of these. This study is conducted in Norway, so we assume these to be roughly similar across the sample of companies in this study. While we expect the results to be generalizable to similar developed countries, socio-economic factors might influence the generalizability of the results to developing countries.

Performance has numerous dimensions. This study mainly focuses on operational performance. This means that other dimensions of performance are not considered in this study, such as environmental and social performance.

1.5 Thesis outline

This thesis is organized into two main parts: the main report (Part I) and the collection of papers (Part II). Part I is based on the research that has been conducted and documented in the appended papers. It gives an overview of the research process and synthesizes the contributions of the independent papers into a coherent argument.

Part I is organized as follows.

Chapter 1 has been the introductory chapter and provided background and motivation for research into this area. It has further outlined the research problem to be investigated and defined research objectives and research questions that will be addressed through this thesis. Finally, it has presented the scope of this study.

Chapter 2 presents the theoretical background related to the topics addressed in this PhD research study. It starts with an overall positioning within the field of manufacturing and operations management, and then further elaborates on the topics of production environments, lean manufacturing, and Industry 4.0. At the end of the chapter, a research framework is presented that was developed to guide the research process.

Chapter 3 concerns the research design of this study. It presents a detailed description of the research methods that have been used, together with reflections on important methodology-related decisions that have been made during the course of the research. Finally, the aspect of research quality is discussed in terms of four established criteria for research quality.

Chapter 4 provides an overview of the results of this research study by providing summaries of the appended research papers that form the basis of this thesis. The chapter starts with a description of the common thread through the papers and outlines their relevance by linking them to the research questions of this thesis. Next, the papers are summarized by presenting their background, purpose, findings, and limitations.

Chapter 5 presents the results from a descriptive case study investigating a number of pilot projects where lean manufacturing practices and digital technologies have been integrated and are working together.

Chapter 6 discusses the findings of this thesis, with a particular focus on addressing the research questions of this study. The contributions of this thesis to theory and practice are also highlighted.

Chapter 7 marks the end of the thesis, and concluding remarks are presented together with the limitations of the research and directions for further research.

Figure 1.1 illustrates the thesis outline and compares it with the commonly used *introduction, methods, results, and discussion* (IMRaD) structure.

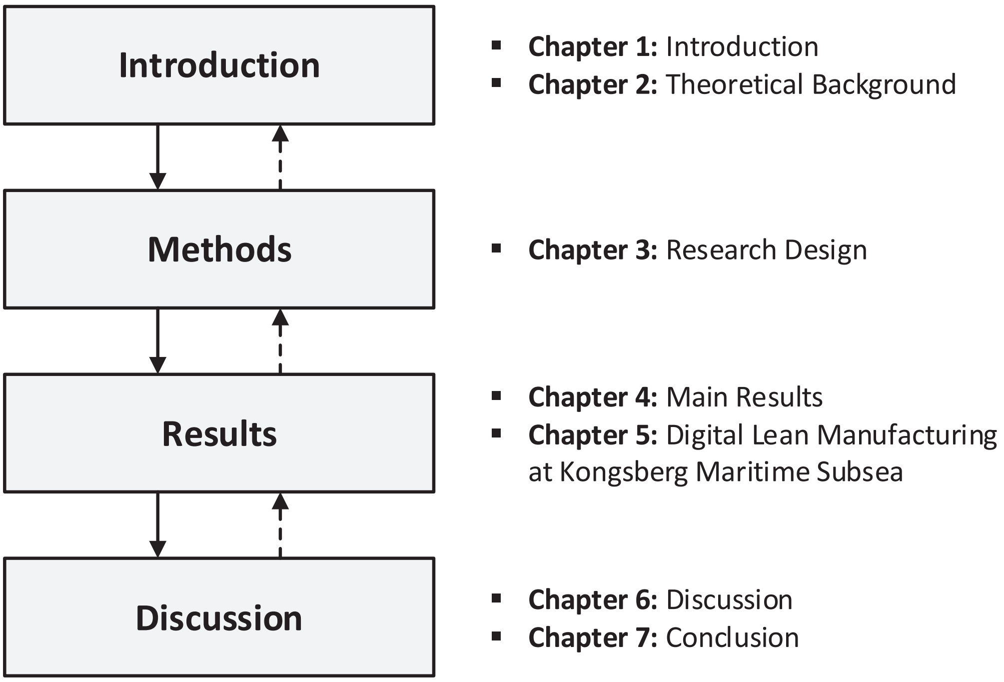


Figure 1.1: Thesis outline according to the commonly used IMRaD structure

Part II includes the papers that were written to disseminate the results from this PhD study. It contains the following six papers:

1. Buer, S.V., Strandhagen, J.O. & Chan, F.T.S. (2018), "The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924-2940.
2. Buer, S.V., Strandhagen, J.W., Strandhagen, J.O. & Alfnes, E. (2018), "Strategic Fit of Planning Environments: Towards an Integrated Framework", *Lecture Notes in Business Information Processing*, Vol. 262, pp. 77-92.
3. Buer, S.V., Alfnes, E., Semini, M. & Strandhagen, J.O. (2019), "New insights on the relationship between lean manufacturing practices and type of production environment", under review at *Production Planning & Control.*
4. Buer, S.V., Strandhagen, J.W., Semini, M. & Strandhagen, J.O. (2019), "The digitalization of manufacturing: investigating the impact of production environment and company size", under review at *Journal of Manufacturing Technology Management.*
5. Buer, S.V., Semini, M., Strandhagen, J.O. & Sgarbossa, F. (2019), "The complementary effect of lean manufacturing and digitalisation on operational performance: results from a survey of Norwegian companies", under review at *International Journal of Production Research.*
6. Buer, S.V., Fragapane, G.I. & Strandhagen, J.O. (2018), "The Data-Driven Process Improvement Cycle: Using Digitalization for Continuous Improvement", *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 1035-1040.

Theoretical Background 2

This chapter introduces the relevant theoretical background for this research study. First, it will introduce how this research positions itself within manufacturing and operations management research. Next, the concept of production environments is introduced together with a motivation for why this aspect is important to consider in research. In the following two sections, lean manufacturing and Industry 4.0 are thoroughly described. Finally, the research framework, which was developed based on theory to guide the research process, is presented.

2.1 Manufacturing

The word manufacturing is derived from the two Latin words *manus* (hand) and *factus* (make) (Groover, 2008). Although goods are typically not solely made by hand anymore, this is the origin of manufacturing. Manufacturing is "a series of interrelated activities and operations involving the design, material selection, planning, production, quality assurance, management, and marketing of discrete consumer and durable goods" (Blackstone, 2013, p. 98). The manufacturing industry has experienced substantial changes in the past and is continuously developing. To summarize these developments, a brief recap of the industrial revolutions is presented.

The first industrial revolution started at the end of the 18th century and introduced major changes to the means of producing goods. It marked the beginning of moving from an agriculture and handcraft-based economy, to one based on industry and manufacturing (Groover, 2008). The invention of the steam engine, machine tools, and the power loom were all important aspects contributing to the first industrial revolution. Factories started to appear, presenting a new way of organizing production (Groover, 2008).

While the first industrial revolution is ascribed to have started in Manchester in the United Kingdom, the second industrial revolution emerged from the United States at the start of the 20th century. The development of the mass production system, enabled by the use of interchangeable parts and the assembly line, increased the output and lowered the manufacturing cost (Klingenberg and Antunes Jr., 2017).

The third industrial revolution was characterized by the increased use of electronics and IT in manufacturing at the start of the 1970s. This enabled the automation of a series of activities that were previously performed manually, including production planning and control (PPC) (Klingenberg and Antunes Jr., 2017). Advanced manufacturing technologies (AMTs) became an umbrella term for the new technologies introduced in different parts of the manufacturing and support processes.

Today, we see the contours of a new industrial revolution known as Industry 4.0. This next industrial revolution will be triggered by rapid advances in IT and internet technology, which allows communication between humans, machines, and components (Brettel et al., 2014). Industry 4.0 will be further discussed in Section 2.5. Figure 2.1 presents an overview of these industrial revolutions.

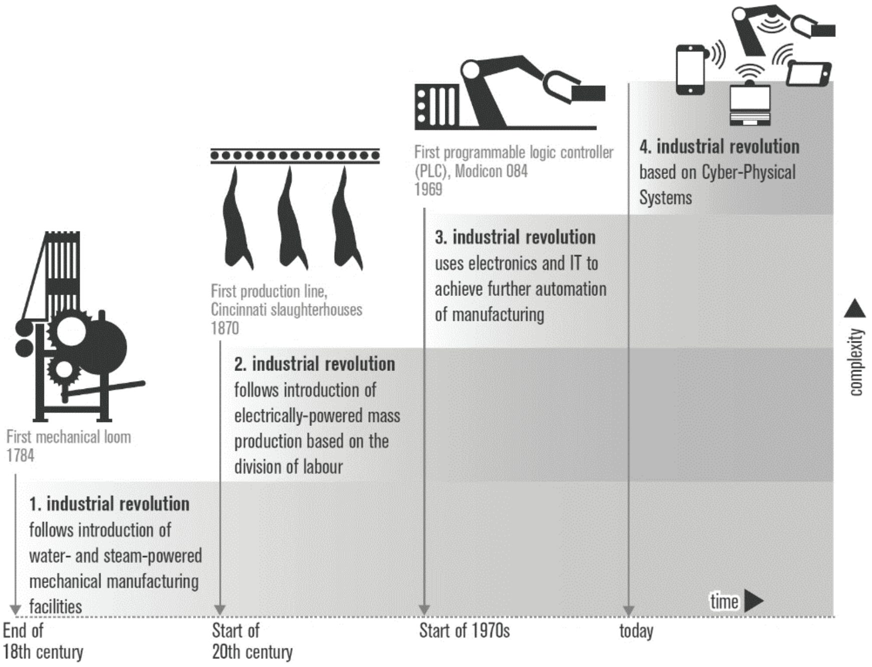


Figure 2.1: The four industrial revolutions (Kagermann et al., 2013)

Manufacturing is traditionally seen as one of the main drivers of economic growth by providing society with goods, jobs, and taxes. In order to maintain their competitiveness, manufacturing companies strive to continuously improve their business processes. Efficient operations management is thus essential.

2.2 Operations management

The field of operations management concerns “effective planning, scheduling, use and control of a manufacturing or service organization” (Blackstone, 2013, p. 115). Like manufacturing, the field of operations management has experienced significant developments.

The roots of operations management are typically traced back to the developments in scientific management and industrial engineering early in the 20th century (Brown et al., 2013). In this context, scientific management means to manage a production system using scientific principles and usually refers to the principles established by Frederick Taylor (Blackstone, 2013). Through his studies on process improvements in American steelworks, he developed several techniques for productivity improvement. While his methods received some criticism, many of the principles he established are still important parts of modern management theories. Using scientific and fact-based methods is the foundation for many of the different improvement approaches proposed throughout the 20th century. These include, for instance, material requirements planning (MRP), which uses numerical techniques to calculate the requirements for materials based on bill of material (BOM) data, inventory data, and the master production schedule (Blackstone, 2013). Other examples include manufacturing resources planning (MRP II), enterprise resource planning (ERP), optimized production technology, quick response manufacturing, total quality management, and lean manufacturing (MacCarthy and Wilson, 2001).

As a result of the manufacturing industry's different industrial revolutions, a larger variety of different types of manufacturing were developed. The second industrial revolution gave us the mass production paradigm and resulted in a larger variety of production environments than previously existed when craft production environments had been dominant. Later, manufacturers specializing in mass customization of products increased this variety even further. The development of customer needs and the emergence of new manufacturing paradigms are illustrated in Figure 2.2. Today, the manufacturing landscape ranges from highly complex one of a kind production to mass production of standard products. The requirements for these companies differ widely, and they typically seek different approaches to managing their operations. Manufacturing companies can be differentiated according to their production environment, an aspect that will be discussed in further detail in the following section.

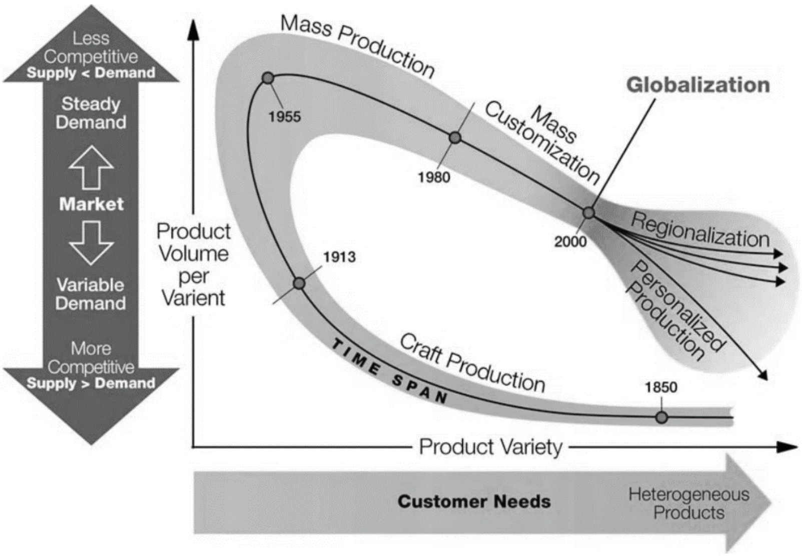


Figure 2.2: Development of customer needs (Koren, 2010)

2.3 Production environments

The contingency theory states that organizations have to adapt their structures to fit with their environment to achieve high performance (Donaldson, 2001; Sousa and Voss, 2008). It is argued that as organizations are individually different and face different situations, different approaches to management are required. While the focus of operations management research for a long time typically focused on describing best-in-class practices, the so-called *best practice paradigm*, the focus has recently shifted toward an interest in understanding under which contextual conditions these practices are effective (Sousa and Voss, 2008). The contingency perspective can explain why some experience significant benefits from certain practices, while others experience implementation difficulties and weaker results than expected. This could be because of a mismatch between the practice and the environment in which it is being implemented. The goal of the contingency perspective is to provide theories that are useful across the spectrum of different contexts. Contingency research should provide guidelines regarding which management practices that are most appropriate for a given context (Sousa and Voss, 2008).

We typically refer to the context in which manufacturing companies operate as their *production environment.* In broad terms, a production environment can be defined as the sum of internal and external variables that influence a manufacturing company's operations (Buer et al., 2018c). It is the environment in which manufacturing strategy is developed and implemented, and includes numerous aspects, such as strategy decisions, product offerings, and product and process design and technology (Blackstone, 2013).

Throughout the years, scholars have proposed numerous frameworks for classifying production environments. Hayes and Wheelwright (1979) proposed to use the two dimensions of *volume* and *variety* to classify manufacturing companies. Their argument was that these two dimensions typically are negatively correlated. That is, manufacturers who produce high volumes of products, typically offer few product variants, whereas manufacturers who offer a large variety of products typically produce in small volumes. They further proposed that volume and variety are related to the type of manufacturing process that is used. Based on this, they proposed the *product-process matrix* (Figure 2.3).

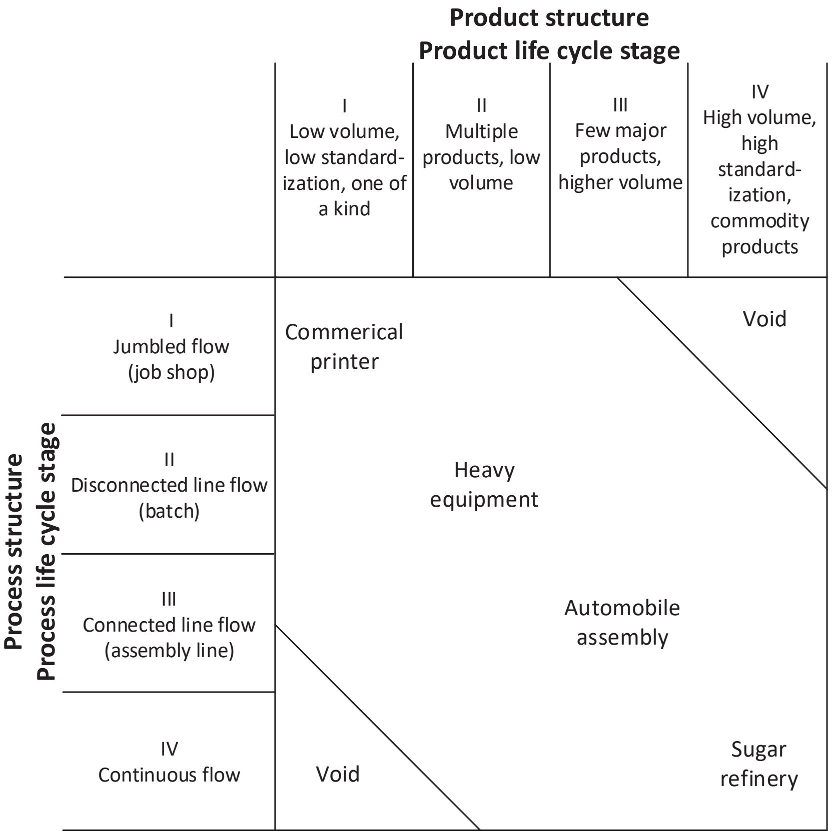


Figure 2.3: The product-process matrix (Hayes and Wheelwright, 1979)

An overall grouping of production environments can be obtained by sorting them based on the placement of the customer order decoupling point (CODP). The CODP can be defined as the point in the manufacturing value chain where the product is linked to a specific customer order (Olhager, 2003). This is arguably the most common categorization of different production environments. The four typical categories are engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS). These are illustrated in Figure 2.4. There have been proposed variations of this typology with even more categories, for instance, the two-dimensional CODP framework by Rudberg and Wikner (2005), which adds additional categories through also considering the engineering process.

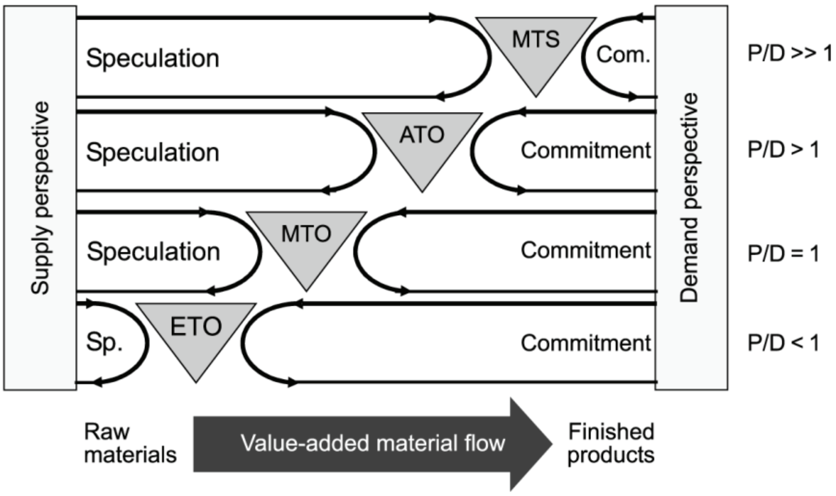


Figure 2.4: The four typical CODPs (Rudberg and Wikner, 2005)

In many studies, companies are categorized merely by their sector or the placement of the CODP. Companies can look significantly different even though they can be grouped in the same sector or if they share CODP placement. For instance, the production environment of a soft drink producer is very dissimilar to that of a cell phone producer, even if both produce to stock. To mitigate this challenge, researchers have proposed more detailed frameworks for classifying different production environments. These frameworks typically consist of a number of internal and external variables and are commonly grouped in three categories: product-, market-, and process-related variables. An overview of different production environment frameworks can be found in Paper 2.

With these numerous environmental variables in mind, and knowing that companies can differ significantly even if they share the placement of their CODP, Jonsson and Mattsson (2003) defined four distinctive groups of production environments: *complex customer order production*, *configure-to-order production*, *batch production of standardized products*, and *repetitive mass production*. This typology is to a larger degree highlighting the differences between production environments than a grouping solely based on the CODP, while simultaneously ensuring strong intra-group similarities. A detailed description of these four groups of production environments can be found in Table 2.1.

Table 2.1: Description of the four types of production environment (Adapted from Jonsson and Mattsson, 2003)

Production environment	Description
Complex customer order production	This type of production implies a low volume, low standardization, and high product variety type of production. The most characteristic feature of this production environment is that the products are more or less designed and engineered to customer order (i.e., it is an ETO type of operation). Manufacturing batch sizes are typically small and equivalent to the customer order quantity. Products are complex with deep and wide bills of material. The manufacturing throughput times and the delivery lead times are long.
Configure-to-order production	The products produced in this environment have less complexity and are assembled in small batches, based on what kind of customization the customer wants. It can be characterized as an ATO or MTO type of operation, where many optional products can be configured and manufactured by combining standardized and stocked components and semi-finished items. The number of customer orders is rather large and the delivery lead times much shorter than for *complex customer order production.*
Batch production of standardized products	This environment can mainly be characterized as MTS of standardized products in medium- to large-sized quantity orders. These products are typically more complex and have a longer lead time than *repetitive mass production.*
Repetitive mass production	In this production environment, products are made in large volumes on a repetitive and more or less continuous basis. It involves standardized products made or assembled from standardized components characterized by having flat and simple bills of materials.

The production environment is known to have implications on a range of different domains in operations management, including the applicability of different PPC methods (Jonsson and Mattsson, 2003), quality management practices (Sousa and Voss, 2001), lean manufacturing practices (White and Prybutok, 2001), and Industry 4.0 applications (Strandhagen et al., 2017). The next two sections will present a detailed introduction to the last two of the listed domains.

2.4 Lean manufacturing

> *"Lean production is 'lean' because it uses less of everything compared with mass production – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time. Also, it requires keeping far less than half the needed inventory on site, results in many fewer defects, and produces a greater and ever growing variety of products."*
>
> Womack et al. (1990, p. 13).

Lean manufacturing has arguably been the most prominent operations paradigm of the 21st century (Found and Bicheno, 2016). The roots of lean manufacturing can be traced all the way back to the development of TPS from 1948 onward (Holweg, 2007). What we today know as lean manufacturing is considered to have originated from the work done at Toyota after the Second World War to establish itself as a leading car manufacturer. This work was led by the industrial engineer Taiichi Ohno. Decades of continuous improvements in their production resulted in the production system known as TPS (Holweg, 2007). However, the development of the work methods at Toyota remained largely unnoticed for a long period of time. Following the oil crisis in 1973, there was renewed interest in researching the future of the automotive industry, and this eventually led to the establishment of the International Motor Vehicle Program (IMVP). Following the research done at this center, as well as the establishment of Japanese automotive manufacturers on US soil, Krafcik (1988) presented the first study that that used the term *lean* to describe the production system that was in contrast with the more traditional mass production system. Through the benchmarking studies conducted as part of the IMVP, researchers found that companies operating with a lean manufacturing system were able to produce a wider range of product variants while maintaining high levels of quality and productivity (Krafcik, 1988). These and other findings from the IMVP were the basis of the book *The Machine That Changed the World* (Womack et al., 1990). This book is considered to be the book that truly popularized the production methods originating from Toyota. However, other relevant works presenting similar ideas were published during the 1980s, but referred to the production system by other names such as *just-in-time* (*JIT) manufacturing* (Schonberger, 1982), rather than lean manufacturing. Since then, the popularity of lean manufacturing has been steadily increasing, which is reflected by the number of books and the volume of research articles on the topic. To clarify, while both the terms *lean production* and *lean manufacturing* are widely used, we do consider these two terms as interchangeable.

The application of lean manufacturing in different industries is growing steadily (Jones and Womack, 2016). There is a consensus that a successful lean manufacturing implementation is associated with improved performance (Mackelprang and Nair, 2010; Marodin and Saurin, 2013). Some of the quantitative benefits of lean implementation documented in literature are improvements regarding "production lead time, processing time, cycle time, setup time, inventory, defects and scrap, and overall equipment effectiveness" (Bhamu and Sangwan, 2014, p. 877). Some of the documented qualitative benefits are "improved employee morale, effective communication, job satisfaction, standardized housekeeping, and team decision making" (Bhamu and Sangwan, 2014, p. 877).

Ohno (1988) describes the two pillars needed to support the TPS: *JIT* and *autonomation* (Jidoka). These pillars are also found in lean manufacturing (Bicheno and Holweg, 2009). JIT refers to a system where parts should be supplied only at the time they are needed and only in the amount needed. By establishing JIT, a company can approach zero inventory (Ohno, 1988). Autonomation, also referred to as "automation with a human touch," is about giving intelligence to the machines so that they can autonomously distinguish between normal and abnormal operations. Therefore, machines will automatically stop if there is a problem, and thus no defective products are produced (Ohno, 1988).

Through the years, lean manufacturing has grown from a focus on JIT and other TPS-specific practices into an overarching philosophy or paradigm of world-class operations (Browning and Heath, 2009). As the lean manufacturing concept has evolved over time, the ambiguity surrounding its definition, what it comprises, and how it should be measured operationally also seems to have increased (Shah and Ward, 2007; Bhamu and Sangwan, 2014). Earlier research has highlighted the ambiguity surrounding lean manufacturing, as well as the challenges arising from this (Pettersen, 2009). As an illustrative example, through their review of 209 research articles, Bhamu and Sangwan (2014) found 33 different definitions of lean manufacturing. In an effort to synthesize earlier research and capture the many facets of lean manufacturing, Shah and

Ward (2007, p. 791) proposed the following definition for lean manufacturing: "Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability."

Lean manufacturing can be seen from different levels. It can be seen from a philosophical level with guiding principles and overarching objectives, and it can be seen from a more operational and practical level with sets of lean manufacturing practices, tools, or techniques (Shah and Ward, 2007). The German standard VDI–2870-1 (2012) presents a framework to illustrate how the overall lean objectives are connected with lean principles, lean practices, and lean tools. Figure 2.5 illustrates the different levels of lean manufacturing operationalization. The following two subsections will first describe the overall perspective on lean and then the more operational perspective in more detail.

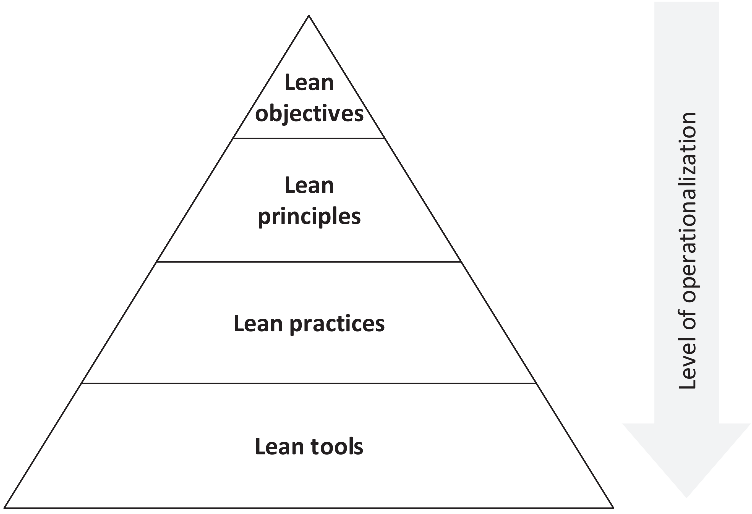


Figure 2.5: Lean objectives, principles, practices, and tools (Adapted from Abdulmalek et al., 2006; VDI–2870-1, 2012)

2.4.1 The overall objectives of lean and the five lean principles

> *"All we are doing is looking at the time line, from the moment the customer gives us an order to the point when we collect the cash. And we are reducing that time line by removing the non-value-added wastes."*
>
> Taiichi Ohno (Cited in Ohno, 1988, p. ix).

There is an agreement that the overall goal of lean manufacturing is to eliminate waste in all forms. In production, waste refers to "all elements of production that only increase cost without adding value" (Ohno, 1988, p. 54). Value is defined from the perspective of the customer. To illustrate, Ohno (1988) defined seven categories of production waste: transport, inventories, movement, waiting, over-production, over-processing, and defects. Another essential aspect of lean manufacturing is continuous improvement. A process is never fully optimized and can always be improved further. Lean manufacturing emphasizes systematic approaches for continuous improvement of all business processes and involving all employees.

In an effort to show that lean is also applicable outside of the automotive industry, Womack and Jones (1996) proposed five lean principles to guide the overall lean thinking that can be applied to almost all types of processes. The five proposed lean principles are as follows:

1. Specify *value* from the customer's perspective.
2. Identify and map *the value stream* and eliminate waste.
3. Create *flow* in the value stream.
4. Establish *pull* based on the rate of customer demand.
5. Seek *perfection* through continuous improvement.

These principles operationalize lean manufacturing to a larger degree than the overall objectives, while still keeping it at such a level of abstraction that it can also be applied outside of a manufacturing context. However, the focus of this thesis is on the manufacturing industry, and it will thus concentrate on the more operational level of lean manufacturing, that is, lean manufacturing practices.

2.4.2 Lean manufacturing practices and tools

From an operational level, lean manufacturing can be seen as an integrated manufacturing system based on the implementation of a diverse set of manufacturing practices. These practices, although diverse, complement each other and interrelate in a way that should result in higher operational performance (Shah and Ward, 2003). There are disagreements in the literature regarding which practices lean manufacturing consists of and how these should be grouped into bundles (Birkie and Trucco, 2016). A prominent example is the TPS "House" (Liker, 2005), which is one of the most well-known lean manufacturing frameworks and illustrates the main aspects of lean manufacturing and how they are related. Pettersen (2009) provides a comprehensive overview of different lean manufacturing typologies from different authors. However, it is a challenging, if not impossible, task to classify one typology as being better than another. The choice of which framework to use is, therefore, often a subjective choice by the researcher, based on that person's understanding of the lean manufacturing concept. Further, in this study, the grouping of lean manufacturing practices by Shah and Ward (2007) is used. Their study aimed at addressing the confusion and inconsistency surrounding the lean manufacturing term. By a thorough investigation of existing research, they developed a set of measurement items that represent the underlying practices of lean manufacturing. Through confirmatory factor analysis, they further refined the measurement instrument. This measurement instrument for lean manufacturing is now well-recognized in research and used directly or adapted in numerous other studies (e.g., Hofer et al., 2012; Azadegan et al., 2013; Bortolotti et al., 2015; Godinho Filho et al., 2016; Tortorella and Fettermann, 2018). They defined a total of 10 lean manufacturing practices, grouped into three categories: *supplier-related practices, customer-related practices,* and *internally-related practices*. As described in the research scope section, the focus of this study is on the internal aspects of a manufacturing company, primarily on what are defined as ILPs. The six ILPs defined by Shah and Ward (2007) are the following: *pull production, continuous flow, setup time reduction, statistical process control (SPC), total productive maintenance (TPM)* and *employee involvement.* As these ILPs will be revisited throughout this thesis, this section will describe each of these in detail.

Pull production

In pull production systems, the product is "pulled" through the system based on the actual demand rate. This implies that an upstream supplier should produce nothing until a downstream customer asks for it (Womack and Jones, 1996). This is valid both internally and externally for the company. The release of orders tries to balance the desired service level with the lowest possible level of work in process (WIP) inventory (González-Rodríguez et al., 2012). One of the primary benefits of operating a pull production system is the reduction of inventory. Toyota merely sees inventory as "… a collection of troubles and bad causes" (Sugimori et al., 1977, p. 557), which is a result of overproduction and hides causes of other types of waste that should be remedied. The reduction of inventory and safety buffers ensures that problems are more easily detected and can be solved.

Kanban is arguably the most well-known method for the operation of a pull production system in practice. Kanban is a simple card-based authorization mechanism that allows the production or movement of products or materials. These cards, called Kanbans, are sent upstream to signal the need for replenishment of a specific product or part. However, Kanban has some known limitations. For instance, it is a suboptimal control mechanism in situations with unstable demand and processing times, non-standardized operations, a large product variety, long setup times for processes, and uncertainty in the supply of raw materials (Junior and Godinho Filho, 2010). To meet the requirements from different types of production environments, new pull production control systems are proposed regularly. In their literature review on token-based (or card-based) pull production control systems, González-Rodríguez et al. (2012) classified 18 different pull production control systems, each designed to operate in a specific type of environment. Notable examples include constant work in process (CONWIP) (Spearman et al., 1990), paired-cell overlapping loops of cards with authorization (POLCA) (Suri, 1998), and control of balance by card-based navigation (COBACABANA) (Land, 2009).

Continuous flow

Continuous flow is about establishing mechanisms that enable and facilitate a continuous flow of products through the production process (Shah and Ward, 2007). A central idea of lean is indeed to shift the focus from maximizing resource efficiency into achieving flow efficiency (Modig and Åhlström, 2012). Continuous flow is typically operationalized as one-piece flow, where the aim is to eliminate batches and produce and transport items in a batch size of one. This supports a reduction in WIP and production lead time. Further, cellular manufacturing presents an alternative to the traditional job shop with the aim to facilitate continuous flow. Grouping functionally dissimilar equipment into a manufacturing cell for the production of a specific product family, research has reported, provides benefits such as improved quality, and job satisfaction, as well as reduced lead time, WIP, and cost (Wemmerlov and Johnson, 1997).

Setup time reduction

Time used for the setup of equipment is considered non-value adding (i.e., waste) and should be reduced according to lean thinking. Reducing the setup times is an important facilitator for achieving one-piece flow without spending excessive amounts of time on changeovers (Karlsson and Åhlström, 1996). The most famous lean manufacturing tool for setup time reduction is the single minute exchange of die (SMED) method developed by Shingo (1985) at Toyota. This name originates from the goal that the changeover of dies should take less than 10 minutes (i.e., a single-digit number of minutes) (Shingo, 1985). SMED offers a systematic approach for analyzing the setup procedure and consequently eliminating unnecessary actions. Further, SMED proposes to do as much of the changeover as possible while the equipment is still running and to simplify and streamline the remaining steps to reduce the required setup time.

Statistical process control

SPC is a practice for quality control using statistical methods to monitor and control a process (Oakland, 2003). The goal is to achieve stable processes that deliver defect-free units to the subsequent process (Shah and Ward, 2007). Central tools for SPC include control charts, cause-and-effect (fishbone) diagrams, and process capability studies (Oakland, 2003). One of the primary benefits of SPC is that it can enable early detection and prevention of quality problems. This is opposed to more reactive quality control mechanisms, such as visual inspection.

SPC can be traced back to the works of Walter Shewhart, who developed the control chart in the 1920s (Woodall and Montgomery, 1999). Shewhart proposed that there are two types of sources of variations in manufacturing processes. The first is common cause variation, which is a variation that is natural to the process and produces a stable, repeatable distribution of time. The second is special cause variation, which is a variation that is not inherent in the system and is intermittent and unpredictable. The former type of variation resembles a process that is “in control,” while the latter resembles a process “not in control” (Fretheim and Tomic, 2015).

Perhaps the most well-known set of tools related to SPC is the Six Sigma methodology, introduced at Motorola in the 1980s. Six Sigma aims at improving the output of a process through identifying and removing the causes of defects and minimizing the variability in the process. It is mainly based on statistical methods, and a Six Sigma process is one where more than 99.99966% of all the output is free of defects. This equals less than 3.4 defect parts per million produced.

Total productive maintenance

Because of the reduction of buffer stocks and the goal of JIT deliveries, equipment reliability is an important aspect of lean manufacturing. TPM is a maintenance approach that aims at optimizing equipment effectiveness, eliminating breakdowns, and promoting autonomous operator maintenance (Nakajima, 1988). With increasing automation and robotization, Nakajima (1988) acknowledged the importance of not only the process’ but also the equipment’s impact on quality. TPM focuses on avoiding unexpected equipment breakdowns and delays, and the ultimate goal is zero breakdowns and zero defects (Nakajima, 1988). Central aspects of TPM include involving the operators in the daily maintenance activities and having a disciplined preventive maintenance plan (McKone et al., 1999).

Employee involvement

To ensure a successful lean manufacturing implementation, it is important to have workers who are motivated, flexible, and eager to contribute to continuous improvement (Groover, 2008). Employee involvement is about engaging all employees in decision-making and continuous improvement processes. Employee involvement should ensure that information and knowledge are transferred from non-management employees to higher-level decision-makers (Yang and Konrad, 2011). Employees should be empowered to make problem-solving decisions at their organizational level. *Kaizen* is a Japanese term which refers to the process of continuous improvement, one of the five main principles of lean. All workers should be involved in Kaizen activities, and given their operational expertise, they are valuable resources for suggesting and implementing improvements (Tortorella et al., 2018b).

Additionally, there are numerous lean manufacturing tools, such as Heijunka, Andon, value stream mapping (VSM), and 5S, which can be said to be on an even lower level of operationalization than lean manufacturing practices. This section has mentioned some of the tools related to specific practices. However, the aim of this chapter is not to give an extensive review of the large number of lean manufacturing tools. A comprehensive overview can be found in Bicheno and Holweg (2009).

2.5 Industry 4.0

"My father's dream! The complete utilization of mechanical power. It's the working out of a model he himself built. A single pressure on a button, and the work of a whole factory begins without anyone to watch or guide it..."

From "The Hidden Colony" (1935) by Otfrid von Hanstein.

Although fully automated factories for some time merely were the topic of science fiction novels, researchers slowly started to embrace this idea. Diebold (1952) coined the word *automation* and presented early ideas on how technology can be used to automate production machinery and processes within a factory. He especially placed emphasis on the notion that inflexible and single-purpose automatic machinery is only suited for a special segment in the market that produces very long production runs of an only slightly varied product. He argued that most companies would benefit from more flexible, general-purpose automatic machinery, and he predicted that the introduction of computers would support these developments.

Advances in computing and automation have previously caused disruptive changes in the manufacturing industry. Arguably the most prominent example in the past was the emergence of the group of technologies known as AMTs (Maghazei and Netland, 2017). AMTs include both hardware-based and software-based technologies, aiming at improving the operating efficiency and effectiveness of the adopting firms (Ehie and Udo, 1996). Examples of technologies commonly associated with AMTs are industrial robots, flexible manufacturing systems, computer numerical control, MRP II, computer-aided manufacturing (CAM), computer-aided design (CAD), and computer-aided engineering (CAE) (Ehie and Udo, 1996; Boyer et al., 1997; Dangayach and Deshmukh, 2005). These technologies should be integrated through advanced computing technology known as computer-integrated manufacturing (CIM) (Ehie and Udo, 1996). While AMTs are typically associated with the third industrial revolution (Maghazei and Netland, 2017), this increased computerization of manufacturing is the foundation which the next industrial revolution will be built on.

Today, the vision of a fourth industrial revolution is emerging, popularly known as Industry 4.0 (Lasi et al., 2014). Industry 4.0, or Industrie 4.0 in German, started as a German government program to increase the competitiveness of their manufacturing industry (Kagermann et al., 2013). It was first announced at the Hannover Messe in 2011 (Drath and Horch, 2014), and is a cooperative project among the private sector, academia, and the German government (Kang et al., 2016). According to the Industrie 4.0 Working Group, Industry 4.0 revolves around "networks of manufacturing resources (manufacturing machinery, robots, conveyor and warehousing systems, and production facilities) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed, and that also incorporate the relevant planning and management systems" (Kagermann et al., 2013, p. 20).

With time, the term Industry 4.0 has evolved into an overall label for describing the next era of manufacturing, and in this process, it has become a poorly defined buzzword for the future of production. Even though Industry 4.0 has been one of the most frequently discussed topics among practitioners and academics in the last few years, no clear definition of the concept has been established; therefore, no generally accepted understanding of Industry 4.0 has yet been published (Brettel et al., 2014; Hermann et al., 2016; Rüttimann and Stöckli, 2016; Hofmann and Rüsch, 2017; Moeuf et al., 2018). To illustrate this divergence, Table 2.2 presents some of the Industry 4.0 definitions found in academic literature. It is obvious that, to increase the robustness of research within this field, researchers and practitioners should agree on a common definition and understanding of the terms.

As shown in Table 2.2, a large variety of definitions exist, from overall strategic perspectives to definitions that focus more on the actual technologies in Industry 4.0. Today, Industry 4.0 can be described as an umbrella term, referring to a range of current concepts and touching several disciplines within industry (Lasi et al., 2014). It can be broadly defined as a vision for the future of manufacturing where a smart manufacturing environment is created by utilizing a large number of emerging, digital technologies. The key drivers for this fourth industrial revolution can be divided into two aspects. The first is the combination of rapidly advancing technological developments of today, such as IoT, IoS, CPS, augmented reality (AR), virtual reality (VR), artificial intelligence (AI), and big data analytics. The emergence and increasing affordability of these technologies is expected to cause a paradigm shift for industrial production (Lasi et al., 2014). This aspect can be described as a technology push. The second aspect is the demand from manufacturing companies, especially in countries with high cost levels, to make oneself independent of high labor costs by exploiting new technology. Businesses will seek new ways of offering their products and services, and new business models will emerge (Kagermann et al., 2013). Reacting to the increased market demand for individualization of products, Industry 4.0 aims at enabling the manufacturing of individual and customized products at the same cost as mass production (Wang, 2016).

Throughout this thesis, different aspects of Industry 4.0 will be highlighted in the different parts of the study and in the appended papers. The following two subsections will give an introduction to Industry 4.0, starting from an overall overview before going into more specific technologies and technology groups.

Table 2.2: Industry 4.0 definitions

	Definition
Anderl (2014, p. 1)	Industrie 4.0 is a strategic approach for integrating advanced control systems with internet technology enabling communication between people, products and complex systems.
Hermann et al. (2015, p. 11)	Industrie 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industrie 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via the Internet of Services (IoS), both internal and cross-organizational services are offered and utilized by participants of the value chain.
Kirazli and Hormann (2015, p. 862)	The systematic development of an intelligent, real-time capable, horizontal and vertical networking of humans, objects and systems. This networking is implemented by utilizing all possibilities of production, information and communication technologies along the entire value-added chain.
Saldivar et al. (2015, p. 1)	The technological evolution from the microprocessor embedded manufacturing systems to the emerging CPS, smartly linking (i) demand to (ii) manufacture, (iii) supply, and (iv) services by the internet. Via decentralising intelligence, object networking and independent process management interact with the virtual and real worlds, heralding a crucial new aspect of future industrial production process that integrates the above four processes.
Schmidt et al. (2015, p. 17)	The embedding of smart products into digital and physical processes. Digital and physical processes interact with each other and cross geographical and organizational borders.
Gilchrist (2016, p. 198)	Industry 4.0 deploys the tools provided by the advancements in operational, communication, and information technology to increase the levels of automation and digitization of production, in manufacturing and industrial processes.
Ivanov et al. (2016, p. 386)	Industry 4.0 represents a smart manufacturing networking concept where machines and products interact with each other without human control.
Monostori et al. (2016, p. 625)	Industrie 4.0 stands for a new way of organization and control of complete value-adding systems. The key objective is to fulfil individual customer needs at the cost of mass production. Therefore it affects all areas from order management, research and development, manufacturing, commissioning, delivery to the use and the recycling of produced goods. The foundation for the new opportunities is the digitization of production with help of cyber-physical production systems. Therefore all involved resources like workers, products, resources and systems have to be integrated as smart, self-organized, cross-corporate, real-time and autonomously optimized instances.
Pfohl et al. (2017, p. 385)	Industry 4.0 is the sum of all innovations derived and implemented in a value chain to address the trends of digitalization, autonomization, transparency, collaboration and the availability of real-time information of products and processes.

2.5.1 Industry 4.0 key features

Because of the different definitions of Industry 4.0, it can be challenging to establish a framework in which a study should take place. The official Industrie 4.0 Working Group highlights three overarching features of Industry 4.0: i) horizontal integration through value networks, ii) end-to-end digital integration of engineering across the entire value chain, and iii) vertical integration and networked manufacturing systems (Kagermann et al., 2013). Additionally, they outline smart products and smart factories as key enablers of the Industry 4.0 vision. Their perspective of Industry 4.0 is thus a smart manufacturing system that is integrated with different business functions and business partners. We follow these recommendations, and this section focuses on introducing the aspects of i) *digitalization of the shop floor* and ii) *technologies for vertical and horizontal integration.* Below are brief descriptions of these two aspects.

Digitalization of the shop floor

A key step to enable digitalization of manufacturing operations is to create smart manufacturing systems: systems that are context-aware and support people and machines in executing shop floor activities by utilizing information from the physical as well as the digital or virtual world (Zheng et al., 2018). Digitalization of the shop floor creates the necessary link for integrating the physical components and resources with the digital world of data and information processing. CPS, and more specifically cyber-physical production systems, is the key element of such a digitalization, as it realizes this integration through the use of sensors, actuators, control processing units, and communication devices (Hofmann and Rüsch, 2017). Sensor and actuator deployment, as well as data collection, can be described as the first two layers of a smart manufacturing system and as the enablers of the data analysis and data-driven decision-making of an Industry 4.0 smart manufacturing system (Zheng et al., 2018). Sensors gather information from the physical world to provide this data as input to higher-level systems that process this information for decision support and decision-making in a smart factory. The increased number of sensors used in equipment and components on the shop floor allows for self-sensing, self-acting, and communication, essentially creating an IoT (Zheng et al., 2018). With a digitalized shop floor, machine and sensor data are collected at the level of the physical objects along the entire value stream, and via a connectivity layer, the gathered data are provided for analytics. Through the integration of these technologies, real-time production data can be collected and shared to facilitate rapid and accurate decision-making through intelligent decision support systems (Ghobakhloo, 2018; Zheng et al., 2018). The access to real-time information on the status and specific changes of components, people, machines, or processes on the shop floor allows for continuous and real-time planning and control of manufacturing operations (Slack et al., 2010).

Technologies for vertical and horizontal integration

Emerging technologies provide improved possibilities for a larger degree of integration, both vertically and horizontally. It should be noted that the use of the terms vertical and horizontal integration, in this case, differ from how they are used in traditional supply chain management (i.e., the acquisition of other business activities).

Vertical integration concerns the integration of various IT systems at the different hierarchical levels inside a factory (e.g., production actuators and sensors, enterprise systems, and product development) and is a main feature of the Industry 4.0 vision (Kagermann et al., 2013). Wang et al. (2016b) emphasized the essentiality of vertically integrating the levels of the automation pyramid, from sensors and actuators on the shop floor, up through the MES and further up to the ERP level. This provides a holistic and integrated management of information and enables a flexible and reconfigurable manufacturing system (Brettel et al., 2014; Wang et al., 2016b). Such a vertical integration, with the expanded utilization of planning tools, software, and IT and the digitalization of manufacturing, has been stated as a requirement to ensure continued competitiveness for the European manufacturing industry (European Commission, 2004).

Horizontal integration refers to "the integration of the various IT systems used in the different stages of the manufacturing and business planning processes" (Kagermann et al., 2013, p. 20). This can be both internally within a company (e.g., from sales forecasting, through production, to warehouse planning and logistics), or among different partners in the value chain (value networks). This integration enables cross-company and company-internal intelligent cross-linking and digitalization of value creation modules (Stock and Seliger, 2016). Horizontal integration through value networks will facilitate inter-corporation collaboration where material flows fluently among these corporations (Wang et al., 2016b). Extensive integration results in increased information sharing, which again facilitates decision-making in the value chain (Fatorachian and Kazemi, 2018).

It should be noted that we use the term *factory digitalization* in Paper 5, which represents the use of digital technologies for internal operations. This construct is composed of the items from the constructs *shop floor digitalization* and *technologies for horizontal and vertical integration* that are related to internal operations. Further details regarding how factory digitalization was mapped can be found in Appendix A of Paper 5.

2.5.2 Digital technologies associated with Industry 4.0

As Industry 4.0 is a broad term with diverse definitions, a wide range of technologies and technology groups have been associated with it. The term *emerging technology* is often used in conjunction with Industry 4.0 and refers to a technology that is quickly growing and has a potential to create significant social or economic effects, but its most prominent impact still lies in the future (Rotolo et al., 2015).

Different studies have attempted to provide a comprehensive overview of the different technologies and technology groups that are associated with Industry 4.0. Because of the large number of different technologies that have been placed under the Industry 4.0 umbrella, this section will not give an extensive review of these. Instead, based on our previous research work presented in Strandhagen et al. (2019), we will give a more general overview of the different technology groups most frequently associated with Industry 4.0. This overview is presented in Table 2.3. These eight technology groups are defined by integrating the work of Mittal et al. (2017), which defines 11 different technology clusters of smart manufacturing, and that of Rüßmann et al. (2015), which defines 9 pillars of technological advances forming the foundation of Industry 4.0.

Table 2.3: An overview of digital technologies typically associated with Industry 4.0 (Strandhagen et al., 2019)

Technology group	Description
Additive manufacturing	3D printing of objects layer by layer, based on a 3D model or CAD file of the object.
Autonomous robots	Automatic guided vehicles, autonomous mobile robots, and collaborative robots for material handling and performing logistics operations.
Cloud manufacturing	Cloud-based solutions for sharing and exchanging data among systems, sites, and companies.
Cyber security	The secure and reliable protection of industrial production systems from cyber threats.
Data analytics	Transforming data into knowledge and actions within a manufacturing system. Big data for analysis of large sets of real-time data, AI, machine learning, and advanced simulations are all part of this cluster.
Integration of IT systems	Horizontal and vertical integration of IT systems for production management (e.g., ERP, MES, and product lifecycle management).
Internet of Things	Objects equipped with sensors and actuators, enabling the storage and exchange of information through network technology.
Visual technology	The visual representation of an object, in the form of AR through superimposing a computer-generated 3D image in the real world, creating a VR, or projecting 3D images as holograms.

2.6 Research framework

By exploring the relevant theory, a research framework can be built in order to guide the further research process. Such a framework explains, typically graphically, the main areas to be studied and the presumed relationships among them (Miles et al., 2013). A research framework should be seen as the researcher's map of the territory that is to be investigated, that is, a tool that will guide the exploration of the research problem. It should be developed at the beginning of the study and be updated as the study progresses (Miles et al., 2013).

As evidenced in the research questions, this study mainly focuses on investigating some of the relationships between four constructs: environmental factors, lean manufacturing, Industry 4.0, and operational performance. Based on the theory presented in this chapter, we can operationalize these constructs further.

Regarding environmental factors, we mainly focus on two aspects: production environment and company size. Regarding production environments, we mainly use the typology developed by Jonsson and Mattsson (2003) introduced in Section 2.3. Concerning company size, we follow the definition presented by the European Commission (2003) concerning small, medium-sized and large enterprises. This means that an enterprise is defined as a small and medium-sized enterprise (SME) if its staff headcount and yearly turnover are less than or equal to 250 and €50 million, respectively. Any enterprise that has either above 250 employees and/or a turnover exceeding €50 million is defined as a large enterprise (LE).

As discussed in Section 2.4, lean manufacturing has many facets and can be defined from different perspectives. In this thesis, we mainly focus on lean manufacturing at the practice-level. We follow the definitions from Shah and Ward (2007) and focus on the internally-related practices.

As discussed in Section 2.5, when it comes to Industry 4.0, new definitions are proposed regularly, and new technologies or technology groups are associated with Industry 4.0. It can thus be challenging to pick an appropriate level of operationalization, as this is such a dynamic domain. We consider the Industry 4.0 features introduced in Section 2.5.1 to be somewhat more stable, as they focus on the capabilities of the system. Therefore, in this thesis, we mainly focus on this level of operationalization. However, individual technologies are also discussed when deemed relevant.

Finally, operational performance can be analyzed in more detail through the five dimensions of performance proposed by Slack et al. (2010): speed, quality, flexibility, dependability, and cost. The research framework is illustrated in Figure 2.6.

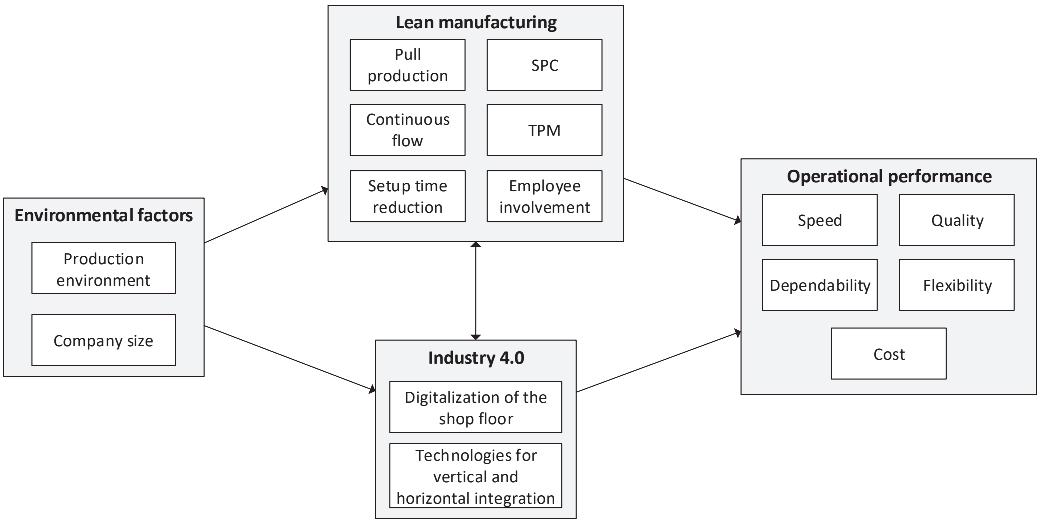


Figure 2.6: Research framework

Research Design 3

This chapter describes the research design of this research study. The first section presents detailed descriptions of the research methods that have been used at different phases in this PhD study, together with reflections on important methodology-related decisions that had to be taken during this research process. In the second section, the aspect of research quality is discussed in terms of four established criteria for research quality.

3.1 Research methods

For the research work presented in this thesis, four research methods have mainly been used. First, a systematic literature review was conducted to map the current knowledge and research gaps regarding the relationship between lean manufacturing and Industry 4.0. Next, to investigate the research gaps related to the applicability of lean manufacturing and of digital technologies across different production environments and their performance implications, a self-administered survey was conducted. Finally, to highlight how lean manufacturing and digital technologies can be combined, we proposed a method for mapping digitalization levels of processes through conceptual development. Additionally, we conducted a descriptive case study to gather and describe empirical examples of such combinations. Furthermore, case data were gathered to test the appropriateness of a proposed mapping framework for production environments. This research thus uses a mix of inductive and deductive research methods. Figure 3.1 provides an overview of the research process of this thesis by showing the overall workflow and the relationships among research questions, research methods, main outcomes, and papers. The following three subsections will explain the main research methods in detail and how the research was conducted.

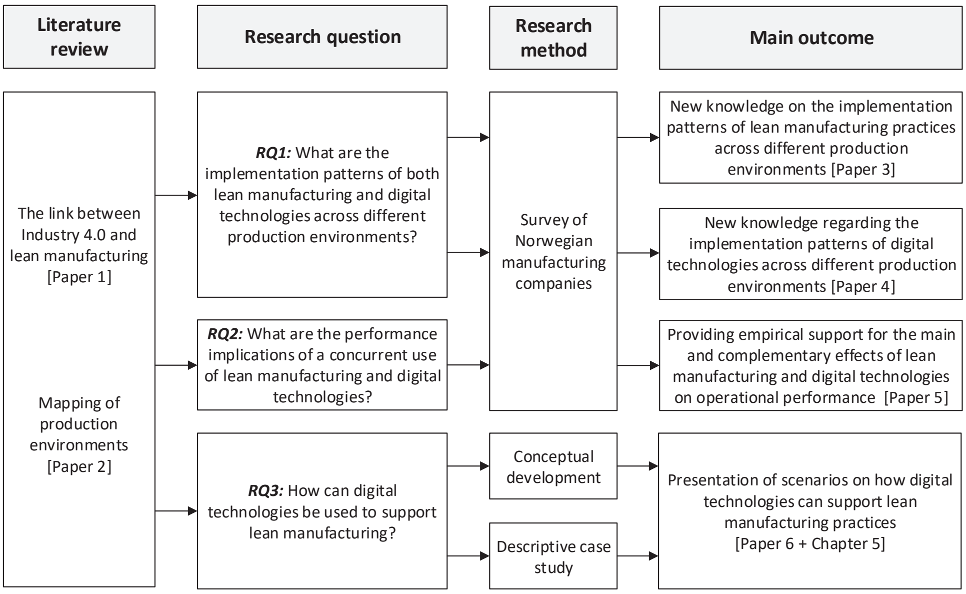


Figure 3.1: The research process of this thesis, showing the relationships among research questions, research methods, main outcomes, and papers

3.1.1 Systematic literature review

A fundamental and natural starting point for any research process is to review the existing literature in the field of interest. It helps to gain an in-depth understanding related to the area, guides the development of hypotheses, research questions, and research scope, and gives justification for the choice of research methodology, and the process itself helps to develop the researcher's research skills (Åhlström, 2016). This makes the literature review an ideal starting point for a PhD study. Therefore, in the initial phase of this research study, a systematic literature review was conducted in order to identify and categorize existing research. The advantage of a systematic literature review is that it ensures replicability by following a series of transparent steps. While the method is thoroughly described in Paper 1, this section will briefly recap the steps and provide some reflective comments on the choices that were made during this research process.

The first step was choosing appropriate search terms. These should reflect the area or research question that you seek to answer. As we sought to map the current research investigating lean manufacturing and Industry 4.0 together, we built a list of search terms consisting of these two blocks. As lean manufacturing is an established term, we presumed that the two terms "lean manufacturing" and "lean production" were sufficient. Regarding Industry 4.0, a much less established domain, we decided to use a larger number of search terms. These search terms were gathered from the seminal Industry 4.0 literature review by Liao et al. (2017). This resulted in a total of 17 different search terms related to Industry 4.0 that can be found in Appendix 1 of Paper 1.

Another important step was establishing inclusion and exclusion criteria (Meline, 2006). This was done to ensure objective reasoning behind the inclusion and exclusion of literature. The inclusion criterion was to look for journal papers, conference papers, and book sections. This was used as a filter in the database searches. Next, we decided on a total of five exclusion criteria. The first four were applied chronologically in the assessment of the abstracts, while the final criterion was used in the assessment of the full texts. The first decision was to exclude all literature not in English, due to the risk of mistranslating. Second, we decided to include only peer-reviewed academic literature. While there certainly are interesting white papers on this topic, these are typically not transparent about their underlying data and research methodology. As a literature review is only as good as the literature input, this criterion was seen as a requirement to ensure a high-quality research result. The third exclusion criterion concerned papers that were not related to Industry 4.0 and lean manufacturing, but for some reason were returned as results in the database searches. The fourth exclusion criterion excluded papers where we were unable to find a full-text version of the paper. For the remaining papers not excluded during this first phase, full texts were assessed. In this phase, papers were excluded if they were only vaguely related to lean manufacturing and Industry 4.0, not providing any specific knowledge on the possible integration of the two domains.

In parallel with the establishment of inclusion and exclusion criteria, relevant databases were identified. As we were looking for peer-reviewed academic literature, five databases, Scopus, ProQuest, Web of Science, ScienceDirect, and EBSCO, were selected. By searching these databases for papers with the search terms defined above in either title, abstract, or keywords, we found a total of 75 unique papers. By screening them based on the criteria listed above, we ended up with 21 papers deemed relevant to include in the literature analysis. These papers were then collected in a database where they were sorted, categorized, and had their main theoretical standpoint and important findings extracted. The software used for this was EndNote X7 for reference management and NVivo 11 for coding the literature.

3.1.2 Survey research

Survey research is the common method used to statistically prove or disprove proposed relationships because of its ability to obtain large sample sizes in a cost-effective way. As *RQ1* and *RQ2* were investigating whether several proposed relationships exist, we decided to use survey research to answer these research questions. While multiple case studies also could be used to investigate these issues, it would require an immense effort to obtain a sample size suitable for statistical analysis.

Surveys require extensive planning to ensure an appropriate research design such that the research questions and related hypotheses can be sufficiently answered or proven, respectively. This section will go through the main steps of conducting a survey and provide descriptions and reflections on how it was done in this research study.

Hypothesis development

The natural starting point of all surveys is to define one or more hypotheses. Typically, this is based on an observed relationship that the researcher wants to test statistically. Existing literature is typically used as support in the hypothesis development to see whether this relationship has been explored before, and in that case, what the results of these studies were. This ensures both practical and theoretical relevance for the planned study.

Survey instrument

After the hypotheses were defined, the next step was to develop a survey instrument reflecting the data collection needs. Based on the constructs we were interested in, we designed a survey instrument with four categories: *company background, mapping of lean manufacturing practices, mapping of digitalization aspects,* and *evaluation of operational performance.* The design of the survey instrument and operationalization of the constructs were mainly based on existing research.

Regarding the first category, company background, the questions were standard background questions regarding the company's sector, number of employees, annual turnover, and the respondent's position. Additionally, based on the production environment typology presented in Table 2.1, descriptions of four characteristic production environments were provided. The respondents were then asked to pick the option that closest resembled their own production environment.

There exist numerous measurement scales to measure the level of lean manufacturing implementation. These range from measurement scales with a few items to extensive measurement scales, for instance, the measurement scale from Shah and Ward (2007) consisting of 41 items. To ensure a thorough and rigorous mapping, the measures from Shah and Ward (2007) were used. As this research focused on the internal aspects of lean manufacturing, we used the measures regarding ILPs. This resulted in a total of 24 items related to mapping the lean manufacturing implementation level, divided into six different ILPs. The respondents were then asked to rate each item on a five-point Likert scale, ranging from (1) no implementation to (5) complete implementation.

Regarding mapping of the implementation of digital technologies, the selection of established measurement scales is scarcer. Further, we identified two challenges that should be considered: a) technological developments are faster than ever, and b) the questions should be easily comprehensible and avoid the most advanced IT jargon. To mitigate these challenges, we decided to focus the questions on the capabilities of the systems, rather than specific technologies. After looking through existing models from literature (e.g., Rockwell Automation, 2014; Lichtblau et al., 2015; Schumacher et al., 2016; Klötzer and Pflaum, 2017; Leyh et al., 2017; Asdecker and Felch, 2018), we decided to use the *PricewaterhouseCoopers Digital Operations Self-Assessment Model* (Geissbauer et al., 2015) as it met the criteria outlined above. As this is a comprehensive framework aiming at evaluating a whole enterprise, we decided to use items from the categories *value chain and processes, IT architecture,* and *organization and culture.* These items were then regrouped to represent the constructs *shop floor digitalization, technologies for vertical and horizontal integration,* and *organizational IT competence*, which were used in Paper 4, as well as the more inclusive term *factory digitalization* used in Paper 5. Similar to those for lean manufacturing, these items were assessed on a five-point Likert scale ranging from (1) no implementation to (5) complete implementation. Since this is an emerging area, the items were additionally supplemented with detailed descriptions and examples.

The respondents were also asked to assess their operational performance level. As operational performance has numerous dimensions, we decided to ask them to assess themselves in five distinct operational performance dimensions: *speed, quality, flexibility, dependability,* and *cost*. These dimensions were operationalized as *production lead time, product quality, process flexibility, process uptime,* and *production cost per unit*, respectively.

The next decision involved determining how the companies should assess themselves. Based on an analysis of earlier similar studies, we observed three typical alternatives for assessing performance:

a. How has your performance changed since implementing lean manufacturing? (e.g., Belekoukias et al., 2014; Panwar et al., 2018),
b. How has your performance evolved over the last five years? (e.g., Shah and Ward, 2003; Ghobakhloo and Hong, 2014), and
c. How does your performance compare to your industrial competitors? (e.g., Cua et al., 2001; Prajogo and Olhager, 2012; Khanchanapong et al., 2014; Zelbst et al., 2014; Chavez et al., 2015).

Regarding *alternative a*, our opinion is that phrasing the question this way might lead to severe bias from the respondent, claiming that the improvement initiative has been more successful than it actually has been. Additionally, it can be difficult to attribute changes in performance to specific implementations, since several improvement initiatives might be running concurrently.

Concerning *alternative b*, choosing an appropriate timeframe is challenging. Lean manufacturing programs might date more than ten years back, while the digitalization initiatives are typically more recent. Assessing performance changes over a time period can, therefore, be challenging when you do not know for certain what has been implemented and when. Additionally, the respondent might have worked in the company for a shorter period of time than what we are asking for and, thus, might not be a reliable source for this information. Nevertheless, we decided to include it in the questionnaire, as it could generate useful data for later analysis. However, it has not been used in the analyses presented in this thesis.

The alternative we decided on was *alternative c*, asking the respondents to rate their performance as compared with their industrial competitors. Although this alternative might also have some drawbacks, for instance, if the respondents were not fully aware of the state of their competitors, we deemed this alternative to be the most appropriate and the best for mitigating the challenges outlined above.

Pilot testing

An important aspect of preparing a survey is to pilot test the survey instrument. This is to check whether the survey will accomplish the study objectives, whether it has sufficient clarity in its questions and alternatives, and whether the questionnaire has a logical buildup. As this questionnaire was based on established measures from other studies, we decided not to run it through extensive pretesting, as we found that these measures had been used successfully in previous studies. After drafting the initial questionnaire together with a master student, it was distributed to two independent colleagues with experience in both research and industry. Based on the recommendations of Forza (2002), they assessed whether the instructions and questions were clear, or if they expected that there would be any problems for the respondents to provide answers or understanding what kind of answers were expected. As a result of their feedback, a few questions were slightly reworded. The survey items can be found in Appendix A.

Establishing a sample

Following the development of the survey instrument, the next step was to establish a sample. The initial sample was obtained from a company database consisting of companies participating in a knowledge-sharing platform for manufacturing logistics. The initial sample consisted of 269 companies. As we aimed to map manufacturing companies, the first filtering step was to remove all companies that did not have their own production, such as design and engineering companies, service companies, and research and development companies. In total, the final sampling frame consisted of 212 manufacturing companies, all located in Norway. There were no restrictions on sector or size, and the final sample contained companies from a wide range of sectors and of different sizes.

Data collection method

Forza (2016) presented four main methods for collecting survey data: mailed survey, personal interview, telephone survey, and electronic survey. The trend is that more and more surveys are done through the internet, either through e-mail or web-based solutions (Forza, 2016). This enables rapid transmission of information, and the collected data can be easily imported into statistical software. These were important factors that ultimately led us to choose a web-based survey. Since web-based surveys are not considered completely anonymous, as IP addresses can be tracked, we had to apply for permission from the Norwegian Centre for Research Data (NSD) to conduct this survey. Based on the data we planned to collect, the NSD found no problematic issues regarding the planned survey and approved the study on the condition that the data were anonymized after the study had ended.

Survey administration

After the survey instrument had been developed, pilot tested, and approved, the survey was sent out to the final sample. The survey was conducted from April to August 2018. It was distributed to the initial sample through e-mails describing the study together with a hyperlink to the survey. The surveys were primarily sent out to a management representative in the company, typically the chief executive officer (CEO), chief technology officer (CTO), production manager, or similar. They were assumed to have the required knowledge to answer the questions in all of the categories. We estimated that it would take from 15 to 20 minutes for the respondents to complete the survey. After two follow-up e-mails, a total of 76 responses were collected through the online survey portal.

Data input and cleaning

After the survey deadline was passed, the data were exported directly from the online survey portal into IBM SPSS 25. For some of the respondents, some data points were missing. The missing data were handled differently based on the extensiveness of the missing data. If only one item was missing in a summated scale, we calculated the average for the scale without sending a follow-up e-mail. This was decided because the reliabilities of the summated scales were of sufficient magnitude (see the section: "Assessing measurement quality"). In the case of missing data for several items within the same summated scale, a follow-up e-mail was sent to that respondent, asking if he or she could supply us with the missing answers. In total, we had to send two such e-mails, and one of these respondents replied and filled in the missing answers. The other respondent, who did not reply to the follow-up e-mail, lacked answers across several of the questions regarding the implementation of lean manufacturing practices. For the analyses using data about the level of lean manufacturing implementation (Papers 3 and 5), this record was removed, while it was kept in the analysis focusing solely on digital technologies (Paper 4). This corresponds to a response rate of 35.4% and 35.8%, respectively. This response rate is higher than average in operations management surveys (Frohlich, 2002) and above the minimum requirements proposed by Malhotra and Grover (1998).

However, we are well aware that this sample size is somewhat smaller than some of the most prominent studies in the operations management field. Getting responses in the hundreds in Norway, a country with a relatively small manufacturing base, proved difficult. In hindsight, we see that we could have tried to gather respondents also from outside of Norway, but that may have introduced some other concerns related to, for instance, differences in national and organizational culture.

To check the data for potential non-response bias, which can limit the generalizability of the results, we compared the responses to the three control variables (i.e., production environment, company size, and length of lean implementation), as well as to five random questionnaire items between the early and late respondents. The chi-square tests for all eight indicated no statistically significant difference between the early and late respondents, with a significance of 0.05. This indicates an absence of non-response bias (Khanchanapong et al., 2014; Chavez et al., 2015).

Assessing measurement quality

As the different papers use slightly different constructs from the survey, this section will not go into detail on the results of the assessment of the measurement quality. In all cases, the data were found to be of sufficient quality, as described in the individual papers. This section will briefly summarize which tests were undertaken and for what reason.

The survey instrument was validated by investigating the *construct validity* and *reliability*. Forza (2002) suggested that two aspects of construct validity should be considered in survey research: *convergent validity* and *discriminant validity*.

Convergent validity is the consistency across measurement items for the same construct. To assess the convergent validity, we first assessed the *unidimensionality* of the measures. This was done through principal component analysis. Following the recommendations of Carmines and Zeller (1979), the constructs were considered unidimensional if the total variance explained exceeded 40% and all of the items' loading factors were above 0.3. To further assess convergent validity, the average variance extracted (AVE) and composite reliability (CR) were calculated for each construct. The recommended threshold for good convergent validity for these two tests are AVE > 0.5 and CR > 0.7 (Hair et al., 2010).

Discriminant validity refers to which degree measures of different concepts are distinct (Forza, 2016). To assess discriminant validity*,* we followed the recommendations of Fornell and Larcker (1981). They stated that, to ensure discriminant validity, the AVE for each construct should be greater than the square of the construct's bivariate correlations with the other constructs.

The most common method for assessing reliability is the Cronbach's coefficient alpha method (Cronbach, 1951; Forza, 2016). It assesses the equivalence, homogeneity, and inter-correlation of the items used to define a construct (Forza, 2016). In the cases where individual items have been combined into a summated scale representing a construct, Cronbach's alpha was estimated to assess their reliability. Forza (2002) suggested a minimum value of 0.6 but recommended that scales should have values above 0.7.

Data analysis
After the data were assessed to be of sufficient quality, the data were analyzed to investigate the proposed hypotheses. The choice of data analysis methods was made *a priori* based on the nature of the hypothesis that was to be investigated. For the hypotheses related to group differences, analysis of variance (ANOVA) was used. For the hypotheses that investigated relationships, multiple regression analysis was used. The different methods have different underlying assumptions that should be met. Before interpreting the results, the data were verified to meet these assumptions. The different analyses are thoroughly described in the papers.

3.1.3 Case study research

Case study research is considered as one of the most powerful research methods in operations management (Voss et al., 2002). The case study investigates a contemporary phenomenon in depth and within its real-world context (Yin, 2013). Observing the phenomenon in its natural setting, the possibility to ask follow-up questions, such as why, what, and how, and the possibility to conduct exploratory investigations on a phenomenon that is emerging and still not fully understood are some of the advantages of case study research (Voss et al., 2002).

Based on the strengths of case study research, we decided to use it on two occasions in this research study. First, it was used to gather case samples to populate the production environment mapping framework presented in Paper 2. Second, to investigate *RQ3*, it was used to gather and describe cases from the industry of how lean manufacturing and digital technologies can be integrated. The findings from this case study are presented in Section 5.

The first case study, that is, the one presented in Paper 2, was a multiple case study to test the production environment mapping framework that was developed based on the literature. As this framework was developed as part of a research project with four industrial partners, these four companies were selected as the initial sample. An additional company connected to another research project was also included, as this company have characteristics which we expected would result in a distinct production environment profiling. The data collection was based on the developed framework consisting of 30 variables. Each company was rated through an interview with a key informant with extensive knowledge of the company, either through employment or through working with the company in research projects. In the cases where the key informant lacked the relevant knowledge to rate one of the variables, this question was passed on to another informant with the required knowledge. After the mapping of the company was completed, the result was verified by a different informant with knowledge of the company.

The second case study, that is, the one presented in Section 5, was a descriptive case study at a manufacturing company producing underwater sensor systems. This case study aimed to describe different pilot projects where lean manufacturing and digital technologies have been successfully integrated and used together. The company was chosen based on its known merits regarding successful use of lean manufacturing, including winning the award *Norwegian Lean Enterprise of the Year* in 2017. This company had recently started to investigate the possibilities offered by digital technologies and had several pilot projects running. It was thus considered a highly relevant case company that provided good opportunities to learn. The case data were collected through semi-structured interviews with representatives responsible for each of the investigated pilot projects. The interview guide can be found in Appendix B. The company's lean program manager was also present during the interviews to add additional information when needed. Additionally, direct observations were used to get a deeper understanding of the solutions. Notes taken during the interviews were used to create a case study description for each pilot project as soon as possible after the interviews were conducted. These case descriptions were then sent back to the interviewees so that they could verify their accuracy.

3.2 Ensuring research quality

To judge the quality of operations management research, Karlsson (2016) proposed four requirements: *construct validity, internal validity, external validity,* and *reliability*. Although these criteria are inspired from quantitative research (Halldórsson and Aastrup, 2003), they have also been proposed to evaluate qualitative research such as case studies (Voss et al., 2002; Yin, 2013). As this research study has used both quantitative and qualitative methods, these four tests were considered adequate to evaluate its research quality. The following subsections elaborate on how these four facets of research quality were considered during the research process.

3.2.1 Construct validity

Construct validity is "the extent to which we establish correct operational measures for the concepts being studied" (Voss et al., 2002, p. 211).

In the preparation of the survey instrument, the face validity of the constructs was assessed in the pilot testing of the questionnaire. The pilot testers gave their assessment of whether the set of questions could be used to measure the constructs that we intended to measure. After the data were gathered from the respondents, we also conducted quantitative tests of construct validity.

These tests were conducted throughout the research process, and descriptions of how this was done can be found in Section 3.1.2 or the individual papers.

In the case studies, two tactics were used to ensure construct validity. First, multiple sources of evidence were used. This included interviews with several key informants and direct observations, which all pointed toward the same conclusion. Additionally, the interviewees were asked to review the draft case study descriptions and could point out any errors or flaws.

3.2.2 Internal validity

Internal validity refers to establishing the correct causal relationships, not overlooking other factors that could explain these relationships (Karlsson, 2016). In other words, if the researcher claim that X has happened because of Y, while it is actually an unacknowledged variable Z that is causing X, the research has low internal validity.

Ensuring internal validity was important both when designing the survey and when analyzing the gathered data. Existing literature was thoroughly reviewed in order to build up a plausible theoretical model. In all of the analysis, there was extensive use of control variables to control for systematic biasing effects of possible confounding variables.

As internal validity is mainly a concern for explanatory case studies seeking to establish causal relationships (Yin, 2013), the exploratory and descriptive nature of the case studies presented in this thesis meant that ensuring internal validity was not a priority in the case study research design.

3.2.3 External validity

External validity refers to whether the results are valid in similar settings outside the study population (Karlsson, 2016), that is, if they can be generalized beyond the studied objects (Voss et al., 2002).

To ensure the greatest generalizability of our research, our sample consisted of companies with a wide range of different characteristics. We also focused on mapping their characteristics to use as control variables in the research. However, as our sample solely consisted of Norwegian companies, we cannot say for certain that our findings can be generalized outside of Norway, although we expect so.

To ensure external validity of case studies, Bryman and Bell (2011) suggested providing “thick descriptions” of the context in which the study has been conducted. Such detailed descriptions enable others to make judgements on whether the research findings are transferable to other situations. We thus aimed at providing detailed descriptions of all the case companies studied in this thesis.

3.2.4 Reliability

Reliability refers to the extent to which a study can be repeated and come to the same results (Voss et al., 2002). The goal is to minimize bias such that the same findings and conclusions could be reached if another researcher replicates the study.

Regarding the survey research, Cronbach’s alpha was estimated for each summated scale to evaluate its reliability. The results from these tests can be found in Papers 3, 4, and 5.

To ensure the reliability of the case studies, a semi-structured interview guide was developed, and the collected data were gathered in a case study database. Additionally, we aimed at having several researchers involved in the research process and in investigating the data, as this may protect against bias from a single researcher.

Main Results

4

This chapter provides a summary of the main results of this PhD research study. This is mainly done by providing summaries of the six appended papers that form the basis of this thesis. The first part of this chapter highlights the common thread through the different papers and outlines their relevance to the research study by linking them to this thesis's research questions. Next, the papers are summarized. Section 4.1 presents the results of a systematic literature review investigating the existing research on the relationship between Industry 4.0 and lean manufacturing, which is reported in Paper 1. As we have so far in this thesis only presented limited theoretical background regarding this relationship, this section is more extensive and clearly outlines earlier findings and the current research frontier. The remaining sections in this chapter briefly summarize the rest of the appended papers by presenting their background, purpose, findings, and limitations.

To support the presentation of the main results and ensure a logical flow of this chapter, the research work is divided into four main research activities. The first research activity is related to highlighting relevant areas for further research by establishing a research agenda. The next three research activities are related to each of the three research questions. Figure 4.1 depicts the research activities and their related papers.

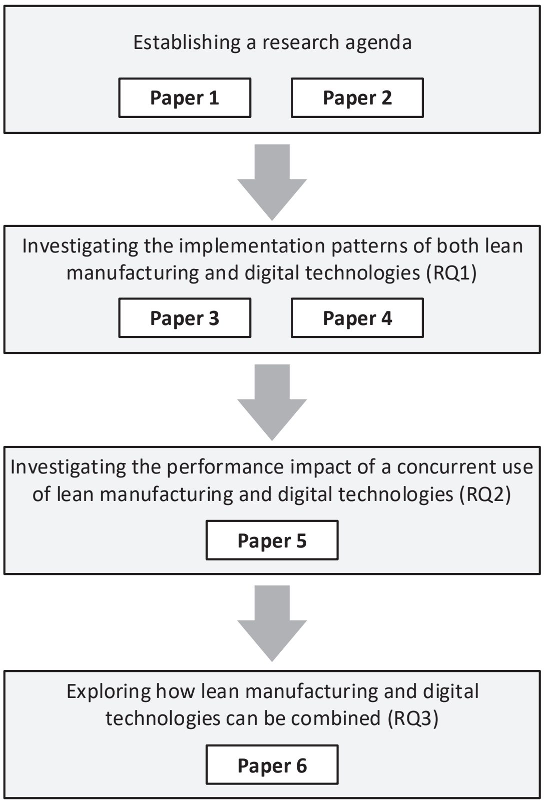


Figure 4.1: The connections between the papers and the main research activities of this study

The first research activity was to establish a research agenda. This was done through a thorough analysis of existing literature to highlight areas we found to be relevant but were insufficiently addressed or answered. The findings from this research activity were used to define more specific research questions (i.e., *RQ1, RQ2,* and *RQ3*), as well as to guide the development of the research framework and the choice of research methods. Based on this, two papers were written. Paper 1 presented the results of a systematic literature review based on analyzing existing literature discussing the relationship between Industry 4.0 and lean manufacturing. We classified existing literature into four main research streams. Additionally, a research agenda for future research on the relationship between Industry 4.0 and lean manufacturing was proposed. Paper 2 presented the results from a study exploring existing frameworks to map a company's production environment (in the paper, we used the term *planning environment*, but we consider these two terms interchangeable). Based on existing frameworks, we proposed an integrated framework for mapping production environments, which included more variables than previous frameworks. Additionally, we emphasized the importance of considering the production environment when conducting empirical research in operations management. The findings in this research activity motivated the research conducted in the following research activities.

The second research activity sought to investigate the implementation patterns of both lean manufacturing and digital technologies; that is, how the implementation levels of these two domains are related to environmental factors. As highlighted in the research framework, this study focused on two environmental factors: production environment and company size. Investigating this issue was important to gain a more in-depth understanding of the current implementation levels of both lean manufacturing and digital technologies in the manufacturing industry. We argue that understanding the applicability of these two domains individually gives valuable insights into which environments they could most easily be combined. To analyze this issue, we used data from the survey described in Section 3.1.2. Two papers were written based on the results of this research activity. Paper 3 investigated the implementation pattern of lean manufacturing, with a particular focus on determining the shape of the relationship between lean manufacturing implementation level and the degree of production repetitiveness. Additionally, we highlighted any group differences in the implementation level between different production environments and company sizes, and the paper thus gives insights into the context-dependency of lean manufacturing practices. Paper 4 used a similar approach to investigate the implementation pattern of digital technologies. To the best of our knowledge, this is the first paper using survey research to investigate differences in the adoption of digital technologies between different groups of production environments. Based on the findings of this research activity, *RQ1* could be answered. Additionally, the paper provided important insights which were used to guide the research approach and discuss the findings of the following research activities.

Motivated by the research need highlighted in the first research activity, the third research activity aimed at investigating the performance impact of a concurrent use of lean manufacturing and digital technologies. Although earlier studies have provided some indications of the performance benefits of such a concurrent use, we have argued that investigating this issue with a rigorously designed survey can provide greater confidence in these findings. Based on the survey results, this study investigated both the main effects of lean manufacturing and factory digitalization on operational performance, as well as their interaction effect. The findings from this research activity are reported in Paper 5. These findings provided input to answer *RQ2*, and the confirmation of both main and complementary effects on performance motivated our further research into why this is the case, and how companies can combine these two domains in practice.

Motivated by the expected benefits of combining lean manufacturing and digital technologies, the final research activity focused on exploring how existing lean manufacturing practices can be enhanced using digital technologies. This research activity consisted of two sub-activities. The first, reported in Paper 6, was to develop a framework which can be used to map the digitalization degree of a process. After analyzing existing literature, we used conceptual development to propose *the data-driven process improvement cycle*. This framework highlights the main steps required for improvement and provides a typology to classify the digitalization degree of these different steps. To illustrate the usage of the framework, the evolution from an analog Kanban system to a self-optimizing Kanban system was described. Second, to highlight how lean manufacturing and digital technologies can be combined, case research with multiple cases from practice was conducted. Based on this, four cases were described, which are presented in Chapter 5. The findings of this fourth research activity contributed to answering *RQ3*. To summarize, Table 4.1 provides an overview of the appended papers, their related research question, and the main outcome.

Table 4.1: An overview of the appended papers, their related research question, and main outcome

Paper number	**Paper title**	**Related research question**	**Main outcome/Result**
Paper 1 (Section 4.1)	The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda	*Overall RQ:* How are lean manufacturing and Industry 4.0 related?	A research agenda for research on lean manufacturing and Industry 4.0 Providing motivation for *RQ1, RQ2,* and *RQ3*
Paper 2 (Section 4.2)	Strategic fit of planning environments: towards an integrated framework	*RQ:* N/A	An integrated framework for mapping different production environments
Paper 3 (Section 4.3)	New insights on the relationship between lean manufacturing practices and type of production environment	*RQ1:* What are the implementation patterns of both lean manufacturing and digital technologies across different production environments?	New knowledge on the implementation patterns of lean manufacturing practices across different production environments and company sizes
Paper 4 (Section 4.4)	The digitalization of manufacturing: investigating the impact of production environment and company size	*RQ1:* What are the implementation patterns of both lean manufacturing and digital technologies across different production environments?	New knowledge on the implementation patterns of digital technologies across different production environments and company sizes
Paper 5 (Section 4.5)	The complementary effect of lean manufacturing and digitalisation on operational performance: results from a survey of Norwegian companies	*RQ2:* What are the performance implications of a concurrent use of lean manufacturing and digital technologies?	Providing empirical support for the main and complementary effects of lean manufacturing and digital technologies on operational performance
Paper 6 (Section 4.6)	The data-driven process improvement cycle: using digitalization for continuous improvement	*RQ3:* How can digital technologies be used to support lean manufacturing?	The data-driven process improvement cycle for mapping current of digitalization levels, as well as planning and guiding improvement processes

4.1 Toward a lean manufacturing and Industry 4.0 research agenda

One of the initial activities of this research study investigating the relationship between lean manufacturing and Industry 4.0 was to identify and categorize existing research on the topic. This was done to ensure the theoretical relevance of the project, as well as to guide the direction of the research. This was achieved through a systematic literature review, as described in Section 3.1.1. First, in Section 4.1.1, a brief overview of the existing research identified in the initial literature review is presented and categorized to illustrate in which areas earlier research was focused. Next, Section 4.1.2 presents a proposed research agenda based on these findings, which has worked as a guideline and provided motivation for the research presented in this study. Finally, as the initial literature review only considered publications up to and including August 2017, Section 4.1.3 presents some of the most relevant recent research in this area.

4.1.1 Mapping current research

To assist in the categorization of existing research on the topic of lean manufacturing and Industry 4.0, we decided to define a classification framework. The framework was built with three sets of variables: the use of practices, environmental factors, and performance, as proposed by Sousa and Voss (2008). The framework is depicted in Figure 4.2. The four relationships in this framework are as follows:

a. Industry 4.0 technologies can support or even enhance existing lean manufacturing practices, that is, *Industry 4.0 supports lean manufacturing.*
b. Established lean manufacturing systems can facilitate Industry 4.0 implementations, that is, *lean manufacturing supports Industry 4.0.*
c. The resulting changes to the production system by the integration of Industry 4.0 and lean manufacturing can affect different performance dimensions of the system, that is, *the performance implications of an Industry 4.0 and lean manufacturing integration.*
d. Environmental factors might influence both the potential to integrate Industry 4.0 and lean manufacturing, as well as the resulting performance, that is, *the effect of environmental factors on an Industry 4.0 and lean manufacturing integration.*

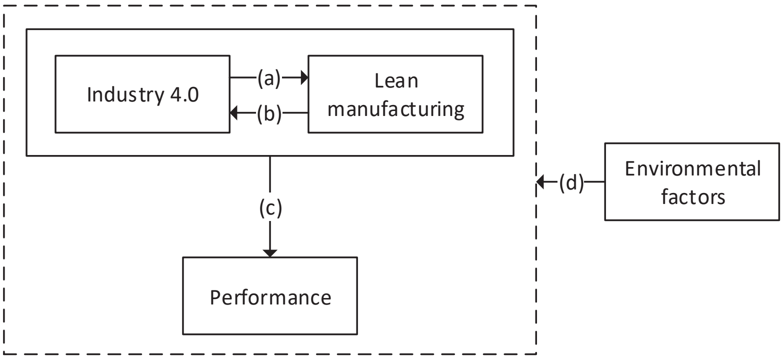


Figure 4.2: Conceptual framework illustrating the relationships among Industry 4.0, lean manufacturing, performance, and environmental factors

Based on these relationships, we proposed four main categories of studies:

1. Studies investigating how Industry 4.0 can support lean manufacturing,
2. Studies investigating how lean manufacturing can support Industry 4.0,
3. Studies investigating the performance implications of an Industry 4.0 and lean manufacturing integration, and
4. Studies investigating the effect of environmental factors on an Industry 4.0 and lean manufacturing integration.

Paper 1 presented an overview of the relevant literature published up to and including August 2017. Based on their focus area(s), these studies are mapped according to the classification framework in Figure 4.3. As observed, the majority of these studies explored how new technological developments associated with Industry 4.0 can support a lean manufacturing system.

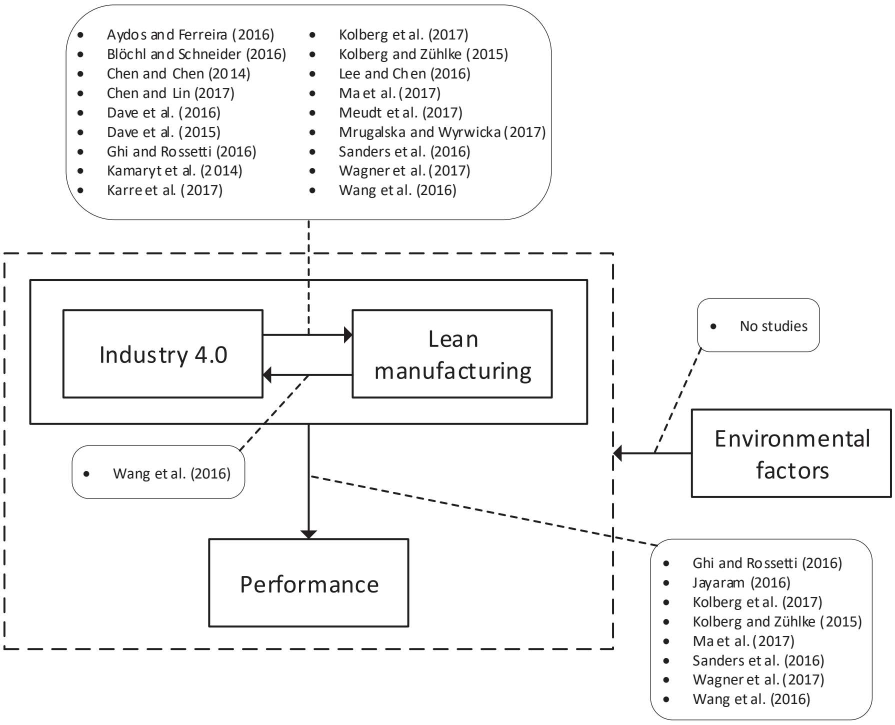


Figure 4.3: Categorization of the papers according to the proposed conceptual framework

Studies investigating how Industry 4.0 can support lean manufacturing

Blöchl and Schneider (2016) have suggested that processes designed according to lean principles can be further improved to deal with higher complexity by using Industry 4.0 technology. Similarly, Wang et al. (2016a) claimed that smart manufacturing can help companies achieve a higher level of lean and investigate the impact on lean manufacturing from technologies related to data collection, big data analysis, and integrated processes. Through a more systematic approach, Wagner et al. (2017) investigated the impact of Industry 4.0 on known lean manufacturing practices. Together with Industry 4.0 and lean manufacturing practitioners, they developed an impact matrix that can assess the potential of integrating different emerging technologies with existing lean manufacturing practices. Karre et al. (2017) described the planned transition of a lean learning factory toward an Industry 4.0 state and presented numerous ideas on how lean manufacturing practices can be enhanced using Industry 4.0 technologies. The analyzed papers present numerous scenarios on how Industry 4.0 and lean manufacturing can be integrated. Table 4.2 summarizes these findings by illustrating which articles discuss the impact of Industry 4.0 on which lean manufacturing practices and tools. The practices and tools presented have been cross-referenced with the lean manufacturing review by Pettersen (2009) to ensure that they are inside the lean manufacturing domain. Table 4.2 further differentiates between "hard" and "soft" lean practices and tools. Hard refers to the technical and analytical practices and tools used in lean, while soft concerns people and relations (Bortolotti et al., 2015). This categorization will be revisited in Section 4.1.2.

Table 4.2: Studies investigating Industry 4.0 impacts on specific lean practices and tools

		Chen and Chen (2014)	Chen and Lin (2017)	Karre et al. (2017)	Kolberg et al. (2017)	Kolberg and Zühlke (2015)	Ma et al. (2017)	Meudt et al. (2017)	Mrugalska and Wyrwicka (2017)	Sanders et al. (2016)	Wagner et al. (2017)	Wang et al. (2016a)
Hard lean practices and tools	Andon				**X**	**X**	**X**		**X**	**X**	**X**	
	Heijunka				**X**						**X**	
	JIT deliveries		**X**		**X**	**X**						
	Kanban		**X**		**X**	**X**		**X**	**X**	**X**	**X**	**X**
	Man-machine separation										**X**	
	One piece flow		**X**	**X**							**X**	**X**
	Poka Yoke					**X**			**X**			
	SMED			**X**		**X**			**X**	**X**		
	Standardized work										**X**	
	SPC			**X**	**X**	**X**				**X**		
	Takted production										**X**	
	TPM			**X**								
	VSM	**X**						**X**	**X**			
	Waste reduction										**X**	
Soft lean practices and tools	5S		**X**								**X**	
	Kaizen								**X**		**X**	
	People and teamwork										**X**	

Studies investigating how lean manufacturing can support Industry 4.0

Of the literature sample we had in this initial literature review, only a single study had investigated how lean manufacturing can support an Industry 4.0 implementation. Wang et al. (2016a) argued that a production process that already has implemented lean manufacturing is more likely to be modelled and controlled. As such, they stressed that this environment is an easier foundation on which to build a smart manufacturing platform.

Studies investigating the performance implications of an Industry 4.0 and lean manufacturing integration

Another main stream in existing research is related to investigating the performance implications of an Industry 4.0 and lean manufacturing integration. This is an important research area because the key area of interest for improvement programs is typically their effect on performance. A number of the identified studies conceptualized the possible performance benefits of an Industry 4.0 and lean manufacturing integration. Others presented empirical research based on experimental demonstrators, case studies, or action research in manufacturing companies.

Through a conceptual study, Sanders et al. (2016) argued that Industry 4.0, together with lean manufacturing, can improve productivity, reduce waste, and, consequently, reduce production costs. Through the use of industrial demonstrators, Kolberg and Zühlke (2015) described how modular workstations and flexible manufacturing lines working together with SMED can reduce setup times. They also argued that autonomous Kanban bins that can detect their inventory level and automatically order parts from suppliers can help reduce inventory levels. Ma et al. (2017) showed how CPS-based smart Jidoka is a cost-efficient and effective approach to improve a production system's flexibility, reliability, and reduce the cost. Table 4.3 illustrates the identified performance benefits reported in the investigated papers.

Table 4.3: Studies evaluating the performance benefits of integrating Industry 4.0 and lean manufacturing

	Conceptual research			**Empirical research**				
Performance dimension	Ghi and Rossetti (2016)	Jayaram (2016)	Sanders et al. (2016)	Kolberg et al. (2017)	Kolberg and Zühlke (2015)	Ma et al. (2017)	Wagner et al. (2017)	Wang et al. (2016a)
Cost			**X**			**X**		
Flexibility			**X**	**X**	**X**	**X**		**X**
Productivity			**X**					**X**
Quality	**X**	**X**						
Reduced inventory				**X**	**X**		**X**	
Reliability						**X**	**X**	

Studies investigating the effect of environmental factors on an Industry 4.0 and lean manufacturing integration

To the best of our knowledge, no studies have explicitly investigated the impact of environmental factors on an Industry 4.0 and lean manufacturing integration. However, some insights can be obtained by analyzing in which sectors the studies have been conducted. Table 4.4 presents an overview of the sectors in which the analyzed studies were conducted. Although this will not give a definitive answer regarding which environments that are suitable for an Industry 4.0 and lean manufacturing integration, it gives some indications regarding in which environments such integrations so far have taken place. In Table 4.4, we can observe that, except for the construction industry, most studies are from typical repetitive production environments.

Table 4.4: Overview of the studies on integrating Industry 4.0 and lean manufacturing in different sectors

Sector	Aydos and Ferreira (2016)	Chen and Chen (2014)	Dave et al. (2016)	Ma et al. (2017)	Wagner et al. (2017)
Automotive				**X**	**X**
Construction			**X**		
Forging	**X**				
Machining	**X**				
Parts manufacturing		**X**			

4.1.2 Establishing a research agenda

Based on what the current body of literature insufficiently addresses or answers, we proposed an agenda for future research. The research agenda consists of five areas for further research. This section will briefly summarize these five research areas, while Paper 1 provides more detailed descriptions of these five areas.

Area 1: The impact of Industry 4.0 on soft lean manufacturing practices

Lean manufacturing is a socio-technical manufacturing system with both hard (technical) and soft (human) aspects. As shown in Table 4.2, most earlier studies have focused on how Industry 4.0 technologies can enhance the hard practices of lean manufacturing. Few studies have focused on how the introduction of Industry 4.0 will impact aspects such as continuous improvement (Kaizen) efforts, teamwork, workforce involvement and autonomy, and 5S. Industry 4.0 will change the manufacturing landscape with an increase in high-skilled jobs (Bonekamp and Sure, 2015). With increasingly dematerialization and virtualization of work processes, there is a risk that workers can experience a loss of control and a sense of alienation from their work. This may result in a loss of creativity and a reduced ability to solve problems in such a digital environment (Kagermann et al., 2013; Hambach et al., 2017). A central question is consequently how the increase in process complexity following an Industry 4.0 transformation will affect the usage of soft lean manufacturing practices and, in turn, how this impacts both the job satisfaction and operational performance.

Area 2: The facilitating effects of lean manufacturing on Industry 4.0 implementations

Another relevant issue to investigate is how an established lean manufacturing system influences the transition toward the Industry 4.0 vision. Building digitalization efforts on a *stable, streamlined,* and *standardized* production system can have several benefits. Having a streamlined production system is important to avoid automating wasteful activities, as this essentially amounts to the automation of waste creation. Streamlined and standardized processes also simplify automation processes. By having an established lean manufacturing system, the organization most likely will have established a continuous improvement culture that actively drives change and has embedded problem-solving structures (Davies et al., 2017). Previous improvement efforts, such as lean manufacturing, could also contribute to reducing employee resistance when management decides to implement new technologies that can be seen as a threat to their positions.

Although the literature gives some indications on the facilitating effects of implementing lean manufacturing prior to an Industry 4.0 transformation, no study has investigated this topic in-depth. The existing studies typically have handled this question at a high level, but without investigating whether there are specific parts of lean manufacturing that are causing this effect. An interesting aspect would be to investigate whether the hard aspects of lean manufacturing, such as the organization of production resources, are the most important ones for this effect or whether it is the soft aspects. Future studies should investigate the reasons behind this phenomenon and how it affects implementation frameworks for Industry 4.0.

Area 3: Empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration

Table 4.3 provides an overview of the studies identified in the systematic literature review discussing the performance impacts of combining Industry 4.0 and lean manufacturing. However, several of these studies only discuss and hypothesize on a conceptual level, while some of the empirical studies collect their data from secondary sources. To motivate an Industry 4.0 and lean manufacturing integration, it is necessary to investigate the performance implications through empirical studies, for instance, using large-scale surveys. Although the current literature of studies gives some indications on the potential performance impacts, the studies are insufficient in both width and depth. Central research issues are to measure what a successful Industry 4.0 and lean manufacturing integration entails, as well as comparing the performance level with those of a “pure” Industry 4.0 or lean manufacturing system.

Area 4: The effect of environmental factors on the integration of Industry 4.0 and lean manufacturing

Environmental factors will be essential both to understand and explain successful integrations of Industry 4.0 and lean manufacturing, as well as the resulting performance of the integration. The literature review identified no studies that focused on the impacts of environmental factors on the integration of Industry 4.0 and lean manufacturing. The sector analysis in Table 4.4 shows that most of the current studies have been conducted in repetitive production environments, similar to where both Industry 4.0 and lean manufacturing were deemed most applicable by earlier studies. Future research should focus on how environmental factors both affect the performance and compatibility of the two domains. These are critical issues to investigate in the endeavor to identify which environments might reap the most substantial benefits of Industry 4.0 and lean manufacturing. An example of a promising research area is whether Industry 4.0 can assist in making lean manufacturing applicable in environments where it previously has been deemed unsuitable.

Area 5: Implementation framework for moving toward an Industry 4.0 and lean manufacturing integration

The immaturity of this research area is a natural explanation for why no implementation framework for an Industry 4.0 and lean manufacturing integration has been published to this point. It is essential to gain a more in-depth understanding of how these two domains interact before an implementation framework can be proposed, and the four prior noted research gaps are all critical in this respect. Future research should focus on investigating whether there is a preferred implementation sequence of the two domains. Should Industry 4.0 and lean manufacturing be implemented concurrently or sequentially? If they should be implemented sequentially, which one should be implemented first? Further, how will the performance be affected by a concurrent or sequential implementation? How do environmental factors influence these issues?

To position the research presented in this thesis, it will mainly focus on research areas 3 and 4. However, these areas are interlinked, and reflections will also be made concerning the other areas where relevant.

4.1.3 Relevant literature published since the submission of Paper 1

As mentioned in Paper 1, the systematic literature review only investigated papers published up to and including August 2017. However, as there is an increasing interest in this area, several relevant papers have been published since then and up to the submission of this thesis. This section will briefly present some of the most relevant recent publications.

We observe that the majority of publications still focus on how Industry 4.0 can be used to enhance existing lean manufacturing practices. This is not surprising as this is arguably the easiest area in which to see the link between Industry 4.0 and lean manufacturing, where there are numerous interfaces which can be explored. Rossini et al. (2019) have investigated the interrelation between the adoption of Industry 4.0 technologies and the implementation of lean manufacturing practices. They found that Industry 4.0 technologies generally have a high degree of correlation with lean manufacturing practices.

Researchers have proposed numerous scenarios on how Industry 4.0 and lean manufacturing can interact. Some publications focused on the more general level. For instance, Mora et al. (2017) presented a theoretical model that visualized the possible intersections between lean manufacturing and Industry 4.0. Additionally, they presented a case where it was explained how a company's Industry 4.0 efforts are linked to lean manufacturing. Similarly, Sony (2018) used a literature review to construct a theoretical integration model for Industry 4.0 and lean management. Additionally, he presented 15 propositions about how Industry 4.0 and lean management can be integrated. Further, both Slim et al. (2018) and Mayr et al. (2018) used conceptual methods to analyze the convergence and contradictions of Industry 4.0 and lean manufacturing, as well as to link Industry 4.0 features to lean manufacturing tools. Romero et al. (2018) studied the interface between digital technologies and lean manufacturing, with a specific focus on waste. They determined that the introduction of digital technologies provides new capabilities for detecting physical waste in production, but also introduces the concept of digital waste. The latter refers to both lost digital opportunities and the overuse of digital technologies.

Other authors have proposed more specific scenarios. Hofmann and Rüsch (2017) discussed the opportunities of Industry 4.0 when it comes to logistics management, with an emphasis on JIT and Kanban systems. They proposed scenarios for how these will develop in the context of Industry 4.0. For JIT systems, they predict that highly transparent and integrated supply chains will reduce bullwhip effects and improve production planning. Regarding Kanban, they foresee an improved demand assessment as well as shortened cycle times. Existing literature further presents a number of examples on how Industry 4.0 technologies can enhance existing lean manufacturing practices and tools (e.g., Dombrowski and Richter, 2018; Powell et al., 2018; Satoglu et al., 2018).

Regarding such combinations of technologies and lean manufacturing practices, the literature mainly reports cases of improving hard lean manufacturing practices, and thus it is easier to find a clear link between the technical and analytical tools of lean manufacturing and the technology-driven paradigm of Industry 4.0. Features such as increased data collection, improved information sharing, flexible machines, autonomous transport solutions, and increased computing power for statistical analysis are all elements that will assist in enhancing the hard lean manufacturing practices. The numerous interfaces have indeed led to some authors claiming that digitalization should be seen as the next step of lean manufacturing (Hoellthaler et al., 2018; Prinz et al., 2018; Hoellthaler et al., 2019).

Regarding how Industry 4.0 will influence the soft aspects of lean manufacturing, research is still lacking. Tortorella et al. (2018b) found that a human-oriented approach, such as employee involvement, does not necessarily conflict with a technology-oriented approach such as Industry 4.0. Further, they determined that the relationship between the implementation of Industry 4.0 technologies and operational performance improvement is mediated by employee involvement. In other words, the impact of Industry 4.0 technologies on operational performance can be enhanced by implementing employee involvement practices. Meissner et al. (2018) further discussed the implications of a digital shop floor management system. Based on a literature review and interviews with experts, they proposed a number of benefits and disadvantages of digitalizing three aspects of shop floor management: performance management, problem-solving management, and leadership on the shop floor.

Recently, studies investigating the performance impacts of an Industry 4.0 and lean manufacturing integration are starting to emerge. By surveying Brazilian manufacturers, Tortorella and Fettermann (2018) found indications that a concurrent implementation of lean manufacturing and Industry 4.0 leads to larger performance improvements than implementing either domain individually. Later, Rossini et al. (2019) conducted a similar study with similar results. In another study of Brazilian manufacturers, Tortorella et al. (2018a) investigated the moderating effect of some Industry 4.0 technology groups on the relationship between certain aspects of lean manufacturing and operational performance. Their results indicated that product and service-related technologies positively moderated the relationship between continuous flow and operational performance, while process-related technologies negatively moderated the relationship between setup time reduction and operational performance. Finally, through a survey of Indian manufacturing firms, Kamble et al. (2019) found that the implementation of lean manufacturing practices has a full mediating effect on the relationship between Industry 4.0 technologies and sustainable organizational performance. Their findings thus indicate that Industry 4.0 technologies in itself do not contribute to improved performance, but rather that these technologies are enablers of lean manufacturing.

As shown above, there are different views in the literature regarding how lean manufacturing and Industry 4.0 interact to impact performance. Additionally, as pointed out by the authors, socio-economic factors in developing countries might have influenced these results. As such, there is still a need for additional research clarifying some of the disagreements in literature, as well as investigating this issue in the context of a developed country.

4.2 Mapping of production environments

Background

Earlier studies have highlighted the importance of achieving a strategic fit between PPC systems and the production environment in which they are implemented (e.g., Rocky Newman and Sridharan, 1995). According to researchers, the lack of such a fit will negatively influence the performance of the manufacturing firm (Berry and Hill, 1992; Jonsson and Mattsson, 2003).

Purpose

Knowing the actual environment in which you operate is the first step toward achieving a strategic fit. Motivated by the importance of achieving a strategic fit and the lack of an established mapping framework, this paper aimed at developing a comprehensive framework for mapping a company's production environment. This framework can then be used as a starting point for selecting appropriate PPC methods, comparing companies, and identifying possible improvement areas.

Findings

Through examining the existing literature, different existing frameworks for mapping production environments were identified and analyzed. Based on the objective of this study, four different frameworks were found to be relevant (Olhager and Rudberg, 2002; Jonsson and Mattsson, 2003; Schönsleben, 2003; Lödding, 2012). Through analyzing their similarities and differences, it was possible to assess the variables that are critical in a production environment mapping process. Three groups of variables were recurring: *product-, market-,* and *manufacturing process-related variables*. These groups and the related variables were used as a basis to develop the integrated framework (Table 4.5), consisting of 30 different variables. By defining values (i.e., alternatives) for each of the variables in the framework, the accessibility and usability of the framework was increased.

We identified six possible usage areas of the proposed mapping framework:

- **Common reference framework:** Since we found no preferred mapping framework in the literature, this could be a candidate for a common reference framework as it is a more comprehensive alternative and integrates different authors' perspectives on how a production environment should be mapped.
- **Initial screening:** The framework can be used to do an initial screening of a manufacturing company to get an overview of their production environment. This can be used as a starting point for further research in the company, especially for externals.
- **Case study tool:** Developed as a matrix, the framework allows for an easy arrangement of the collected data, detailed analysis, and cross-case analysis (Miles et al., 2013). Since the standardization of values for each variable simplifies cross-case analyses, it could be argued that this makes the framework more appropriate for multiple case studies than for single case studies. However, the framework can easily be adapted to an in-depth single case study by making the values more exact, for instance, by giving the exact number of product variants.
- **Benchmarking:** By using the framework to map different companies, it is easy to compare them and identify similarities and differences. This way, it could also be used as a benchmarking tool to compare a company with, for instance, another company that is considered "best-in-class."
- **Causality between variables:** The paper presents a causality matrix where the expected causality among the variables is presented. This can work as a decision support tool for change processes. For instance, if a company experiences that a variable changes state, either because of changes in the company's own structure or because of external influences, the matrix gives input on which other variables might be influenced and possibly also need to be adjusted to better conform to the new premises.
- **Company profiling:** When mapping a company, the framework is structured in a way such that companies clearly should see a pattern, a so-called company profiling, when populating the framework. This is similar to the product profiling concept (Hill, 1995). Briefly explained, the framework can be used to analyze the match between product and market characteristics and the manufacturing process choices. The resulting profiling will identify any mismatches and therefore highlight the areas that should be looked into for better conformance among the different groups of characteristics (Hill, 1995). The framework can thus be used as a decision support tool. Companies that produce complex, customized products see that the majority of their variables typically correspond to the values on the left side of the framework. On the other hand, companies that mass-produce standardized products find that their variables typically correspond to values on the right side of the framework. However, we expect that three of the variables (marked in the framework) are not dependent on the production repetitiveness of the company and should be ignored when using the framework as a profiling tool.

To test the developed framework, we collected case samples from five manufacturing companies with widely different characteristics. This testing confirmed the framework's accessibility and usability and provided rich descriptions of each of the five companies, which have served as an excellent platform for further research in these companies. The framework itself and the mapping of the companies are presented in Table 4.5.

Limitations

The development of the framework and the sorting of the variables and values were primarily based on literature and conceptual analysis. Additional insights on the causality among the variables might be obtained through, for instance, an extensive survey of a wide range of manufacturing companies. While this framework maps the production environment, it does not provide specific suggestions for appropriate PPC methods.

Table 4.5: Integrated framework for mapping the production environment

<table>
<tr><th></th><th>Variable</th><th colspan="6">Values</th><th>Ref.</th></tr>
<tr><td rowspan="6">Product-related</td><td>CODP placement</td><td>ETO
A, B</td><td colspan="2">MTO
B, C</td><td colspan="2">ATO</td><td>MTS
D, E</td><td>[1,2]</td></tr>
<tr><td>Level of customization</td><td colspan="2">Fully customer specific
A</td><td colspan="2">Some specifications are allowed
B, C, E</td><td colspan="2">None
D</td><td>[1]</td></tr>
<tr><td>Product variety</td><td colspan="2">High
A, B, C, E</td><td colspan="2">Medium</td><td colspan="2">Low
D</td><td>[1,3, 4]</td></tr>
<tr><td>BOM complexity</td><td>More than 5 levels
A, E</td><td colspan="2">3-5 levels
B</td><td colspan="2">1-2 levels and several items
C</td><td>1-2 levels and few items
D</td><td>[1,2, 4]</td></tr>
<tr><td>Product data accuracy</td><td colspan="2">Low
A, B</td><td colspan="2">Medium
A, B, C</td><td colspan="2">High
C, D, E</td><td>[1]</td></tr>
<tr><td>Level of process planning</td><td colspan="2">None</td><td colspan="2">Partial process planning
A, C, E</td><td colspan="2">Fully designed process
B, D</td><td>[1]</td></tr>
<tr><td rowspan="10">Market - related</td><td>P/D ratio</td><td colspan="2"><1
A, B, C</td><td colspan="2">1</td><td colspan="2">>1
D, E</td><td>[1]</td></tr>
<tr><td>Demand type</td><td colspan="2">Customer order allocation
A, B, C</td><td colspan="2">Calculated requirements</td><td colspan="2">Forecast
D, E</td><td>[1,2]</td></tr>
<tr><td>Source of demand</td><td colspan="3">Customer order
A, B, C, D, E</td><td colspan="3">Stock replenishment order
D, E</td><td>[1]</td></tr>
<tr><td>Volume/ frequency</td><td>Few large customer orders per year
A, B</td><td colspan="2">Several customer orders with large quantities per year</td><td colspan="2">Large number of customer orders with medium quantities per year
C, D, E</td><td>Frequent call-offs based on delivery schedules</td><td>[1,4]</td></tr>
<tr><td>Frequency of customer demand</td><td>Unique
A, B</td><td colspan="2">Block-wise or sporadic
B, C, E</td><td colspan="2">Regular
C, D, E</td><td>Steady (continuous)</td><td>[2]</td></tr>
<tr><td>Time distributed demand</td><td colspan="3">Annual figure
A, B, E</td><td colspan="3">Time distributed
C, D</td><td>[1]</td></tr>
<tr><td>Demand characteristics (*)</td><td colspan="3">Dependent
B</td><td colspan="3">Independent
A, C, D, E</td><td>[1]</td></tr>
<tr><td>Type of procurement ordering (*)</td><td colspan="3">Order by order procurement
A, B, C, D, E</td><td colspan="3">Order releases from a delivery agreement
C, D</td><td>[1]</td></tr>
<tr><td>Inventory accuracy (*)</td><td colspan="2">Low</td><td colspan="2">Medium
A, B, C</td><td colspan="2">High
D, E</td><td>[1]</td></tr>
</table>

Table 4.5: Integrated framework for mapping the production environment (continued)

<table>
<tr><th></th><th>Variable</th><th colspan="60">Values</th><th>Ref.</th></tr>
<tr><td rowspan="15">**Manufacturing process-related**</td><td>Manufacturing mix</td><td colspan="30">Mixed products
A, E</td><td colspan="30">Homogenous products
B, C, D</td><td>[1]</td></tr>
<tr><td>Shop floor layout</td><td colspan="15">Fixed-position
A, B</td><td colspan="15">Functional
C, E</td><td colspan="15">Cell
B</td><td colspan="15">Product
D</td><td>[1,2,3,5]</td></tr>
<tr><td>Type of production</td><td colspan="15">Single unit production
A, B, E</td><td colspan="15">Small series
B, E</td><td colspan="15">Serial production
C</td><td colspan="15">Mass production
D</td><td>[2,3]</td></tr>
<tr><td>Throughput time</td><td colspan="12">Years
A</td><td colspan="12">Months
A, B, E</td><td colspan="12">Weeks
B, C</td><td colspan="12">Days
C, D</td><td colspan="12">Hours
D</td><td>[1]</td></tr>
<tr><td>Number of major operations</td><td colspan="20">High
A, B, E</td><td colspan="20">Medium
C</td><td colspan="20">Low
D</td><td>[1]</td></tr>
<tr><td>Batch size</td><td colspan="15">Equal to customer order quantities
A, B, C</td><td colspan="15">Small, equal to one week of demand
E</td><td colspan="15">Medium, equal to a few weeks of demand
D</td><td colspan="15">Large, equal to a month’s demand or more
D</td><td>[1]</td></tr>
<tr><td>Frequency of production order repetition</td><td colspan="20">Non-repetitive production
A</td><td colspan="20">Production with infrequent repetition
B</td><td colspan="20">Production with frequent repetition
C, D, E</td><td>[2]</td></tr>
<tr><td>Fluctuations of capacity requirements</td><td colspan="20">High</td><td colspan="20">Medium
A, B, C, E</td><td colspan="20">Low
D</td><td>[3]</td></tr>
<tr><td>Planning points</td><td colspan="20">High
A</td><td colspan="20">Medium
B, C, E</td><td colspan="20">Low
D</td><td>[4]</td></tr>
<tr><td>Setup times</td><td colspan="20">Low
C, E</td><td colspan="20">Medium
A, B</td><td colspan="20">High
D</td><td>[1,4]</td></tr>
<tr><td>Sequencing dependency</td><td colspan="15">None</td><td colspan="15">Low
C, E</td><td colspan="15">Medium
A, B</td><td colspan="15">High
D</td><td>[1]</td></tr>
<tr><td>Part flow</td><td colspan="15">One-Piece-Flow
A, B</td><td colspan="15">Overlapped
E</td><td colspan="15">Lot-Wise
B, C, D</td><td colspan="15">Bulk (Batch)</td><td>[3]</td></tr>
<tr><td>Material flow complexity</td><td colspan="20">High
A, E</td><td colspan="20">Medium
B, C</td><td colspan="20">Low
D</td><td>[3]</td></tr>
<tr><td>Capacity flexibility</td><td colspan="20">High</td><td colspan="20">Medium
C</td><td colspan="20">Low
A, B, D, E</td><td>[3]</td></tr>
<tr><td>Load flexibility</td><td colspan="20">High
A</td><td colspan="20">Medium
B, C, E</td><td colspan="20">Low
D</td><td>[3]</td></tr>
<tr><td colspan="63">Notes: (*) Not dependent on production environment; A: Kleven; B: Brunvoll; C: Ekornes; D: Pipelife; E: Kongsberg Maritime Subsea; [1] (Jonsson and Mattsson, 2003); [2] (Schönsleben, 2003); [3] (Lödding, 2012); [4] (Olhager and Rudberg, 2002); [5] (Slack et al., 2010)</td></tr>
</table>

4.3 The implementation pattern of lean manufacturing

Background

Although originating from the automotive industry, lean manufacturing is expanding into other industries, and today, lean manufacturing practices can be observed in every industry. Yet, the extent of the actual diffusion across the industrial spectrum is not definitely known (Shah and Ward, 2003). Previous studies have investigated the differences in the implementation level of lean manufacturing between repetitive and non-repetitive production systems (White and Prybutok, 2001), discrete and process manufacturing (Shah and Ward, 2003), and MTO and MTS production (Olhager and Prajogo, 2012). However, common to these studies is that they treat the production environment as a dichotomous variable, that is, a variable with only two categories. We argue that the production environment is too complex a variable to be defined only by two categories and that a more precise categorization of production environments should be used. This way, more nuanced results regarding the applicability of lean manufacturing across different production environments can be obtained.

Purpose

This study aimed at investigating the universality of lean manufacturing. This was done in two steps. First, the shape of the relationship between production repetitiveness and lean manufacturing implementation level was investigated. Second, the data were analyzed to uncover any significant group differences among different production environments regarding the implementation level of lean manufacturing and individual lean manufacturing practices.

Findings

The data used in this study were collected through a survey of Norwegian manufacturing companies. This process is described in Section 3.1.2. First, to investigate the shape of the relationship between production repetitiveness and lean manufacturing implementation level, a hierarchical regression analysis was conducted. The production repetitiveness variable was constructed by coding the four different production environments (presented in Section 2.3) into a four-point scale, where *complex customer order production* equals 1 (least repetitive), and *repetitive mass production* equals 4 (most repetitive). A total of three models were tested. Model 1 investigated only the effect of the control variable (i.e., company size) on the dependent variable (i.e., lean manufacturing implementation level). Model 2 added the predictor variable production repetitiveness. Finally, Model 3 added curvilinearity to the analysis by adding the squared term of production repetitiveness to the regression analysis.

Table 4.6: Results from the hierarchical regression analysis^a

	Dependent variable: Lean manufacturing implementation level		
	Model 1	**Model 2**	**Model 3**
Company size (control)	0.138	0.120	0.073
Production repetitiveness		0.245*	0.313**
Production repetitiveness^2			–0.297*
***F*-value**	1.416	3.070†	4.519**
R^2	0.019	0.079	0.160
Adj. R^2	0.006	0.053	0.125
Change in R^2		0.060*	0.081*

Notes: †<0.10; *$p < 0.05$; **$p < 0.01$; ^{a}Standardized regression coefficients are reported.

As shown in Table 4.6, Model 1 explains only a negligible amount of the variance in the lean manufacturing implementation level, suggesting that factors other than company size are responsible for this variance. Adding production repetitiveness (Model 2) and the squared term of production repetitiveness (Model 3) produced significant improvements to the model (cf. the change in R^2). Model 2 shows a significant relationship between production repetitiveness and the lean manufacturing implementation level, suggesting that the former is a significant predictor of the latter. However, as adding the quadratic term to the model resulted in a significant improvement to the model, this suggests that the relationship is not linear, but rather curvilinear. By observing that the linear term has a positive sign, while the squared term has a negative sign, we can conclude that the shape of the regression curve resembles an inverted U-shaped curve. This is illustrated in Figure 4.4, which shows the scatter plot of the collected survey data and the quadratic regression line. It highlights the decline in implementation level on both ends of the production repetitiveness scale, a phenomenon that has not been described in earlier, similar studies. The inverted U-shaped curve suggests that the degree of production repetitiveness is among the most important factors that can explain the differences in lean manufacturing implementation level among different manufacturing companies.

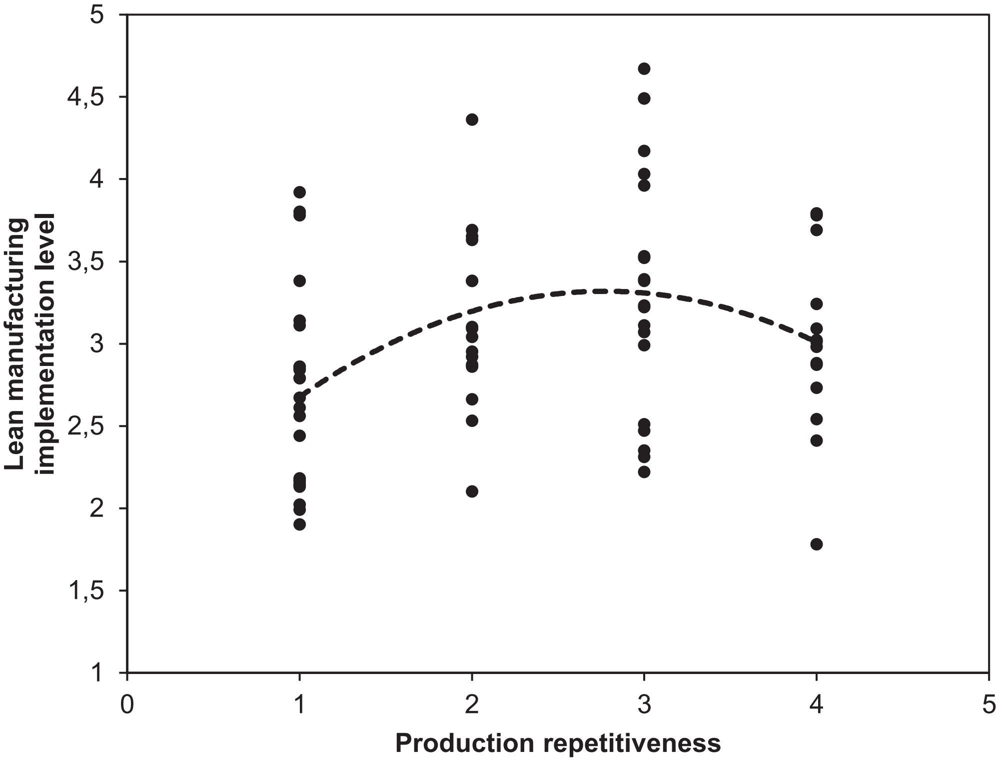


Figure 4.4: The inverted U-shaped curve of lean manufacturing implementation levels

The inverted U-shaped curve provides a guideline for the applicability of lean manufacturing across different production environments. This can be used by practitioners to identify the company's position on the repetitiveness scale to obtain a realistic perspective on which levels of lean manufacturing are obtainable. Practitioners should use the inverted U-shaped curve to adjust their targets, expectations, and approach for their lean manufacturing implementation process, rather than trying to force through a standardized implementation program. A relevant example is that of standardized lean manufacturing programs in large organizations with numerous plants with different characteristics. The inverted U-shaped curve illustrates that these implementation programs should be adjusted based on the plant's production environment. This includes adjusting both the implementation process and the implementation level target.

Second, a two-way ANOVA was conducted to uncover any group differences between different production environments and company sizes regarding the implementation levels of lean manufacturing and individual ILPs. The advantage of this method is that it can simultaneously investigate and control for group differences in two independent or grouping factors. Thus, it would very likely determine whether any unique interaction effects between production environment and company size resulted in an especially high or low mean value for any of the lean manufacturing practices.

For one of the ILPs, continuous flow, there was a statistically significant interaction between production environment and company size ($p < 0.1$). As this was a disordinal interaction, the interpretation of main effects could be misleading (Fox, 2016), and continuous flow was thus omitted from Table 4.7 and Table 4.8. Instead, an analysis of simple main effects was performed. This analysis indicated a significant difference in the implementation level of continuous flow between the production environments *complex customer order production* and *configure-to-order production*, but only for LEs ($p < 0.01$). Additionally, a significant difference in the implementation level of continuous flow was found between SMEs and LEs, but only for companies in the *configure-to-order production* group ($p < 0.1$).

For the remainder of the dependent variables, no significant interaction effects were found, allowing the interpretation of the main effects. The results from the two-way ANOVA are presented in two separate tables. In Table 4.7, the results regarding differences in the implementation level of lean manufacturing practices across the different production environments are presented. A statistically significant difference in the lean manufacturing implementation level was found. Similarly, statistically significant differences were found for the ILPs setup time reduction and SPC. In all three cases, the significant pairwise comparison (Tukey–Kramer post hoc analysis) uncovered that the significant difference was between *complex customer order production* and *batch production of standardized products*. In all three cases, *complex customer order production* had the lowest level of implementation.

Table 4.7: Results of the two-way ANOVA (production environment)

	A. Complex customer order production	**B. Configure-to-order production**	**C. Batch production of standardized products**	**D. Repetitive mass production**	**ANOVA**	**Significant pairwise comparisons[a]**	**Effect size[b]**
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**	***F*-value**		
Lean manufacturing implementation level	2.69 (0.59)	3.14 (0.54)	3.35 (0.76)	2.99 (0.55)	3.606*	[A,C]**	0.134
Pull production	2.24 (0.87)	2.78 (0.87)	2.80 (0.80)	2.34 (1.02)	1.915		0.076
Setup time reduction	2.62 (0.90)	3.25 (0.98)	3.55 (0.84)	3.25 (0.65)	4.638**	[A,C]**	0.164
SPC	2.28 (0.88)	2.65 (0.99)	3.33 (1.10)	2.76 (0.84)	3.227*	[A,C]**	0.111
TPM	3.00 (0.93)	3.36 (0.88)	3.65 (0.91)	3.00 (0.94)	1.507		0.059
Employee involvement	3.03 (0.64)	3.19 (0.47)	3.41 (0.94)	3.27 (0.83)	0.725		0.031

Notes: $*p < 0.05$; $**p < 0.01$; [a]Using Tukey–Kramer post hoc test; [b]Reports eta-squared (η^2); effect sizes from eta-squared: small = 0.01–0.06, medium = 0.06–0.138, large > 0.138

Table 4.8 presents the two-way ANOVA results related to differences in implementation between SMEs and LEs. As shown, the differences in implementation level between SMEs and LEs are mostly minor. The only statistically significant difference was found for the implementation level of SPC, where LEs had the highest implementation level.

To summarize, the results from the two-way ANOVA are illustrated in Figure 4.5. The figure illustrates the context-dependency of the ILPs, that is, whether their implementation level is related to the type of production environment and the size of the company.

Table 4.8: Results of the two-way ANOVA (company size)

	SMEs	**LEs**	**ANOVA**	
	Mean (*SD*)	**Mean (*SD*)**	***F*-value**	**Effect size[a]**
Lean manufacturing implementation level	2.92 (0.55)	3.11 (0.75)	0.491	0.006
Pull production	2.56 (0.90)	2.49 (0.92)	0.796	0.011
Setup time reduction	3.19 (0.80)	3.05 (1.03)	1.268	0.015
SPC	2.41 (0.85)	3.03 (1.09)	5.376*	0.061
TPM	3.00 (0.91)	3.48 (0.92)	2.779	0.036
Employee involvement	3.17 (0.70)	3.24 (0.78)	0.001	0.00002

Notes: *$p < 0.05$; [a]Reports eta-squared (η^2); effect sizes from eta-squared: small = 0.01–0.06, medium = 0.06–0.138, large > 0.138

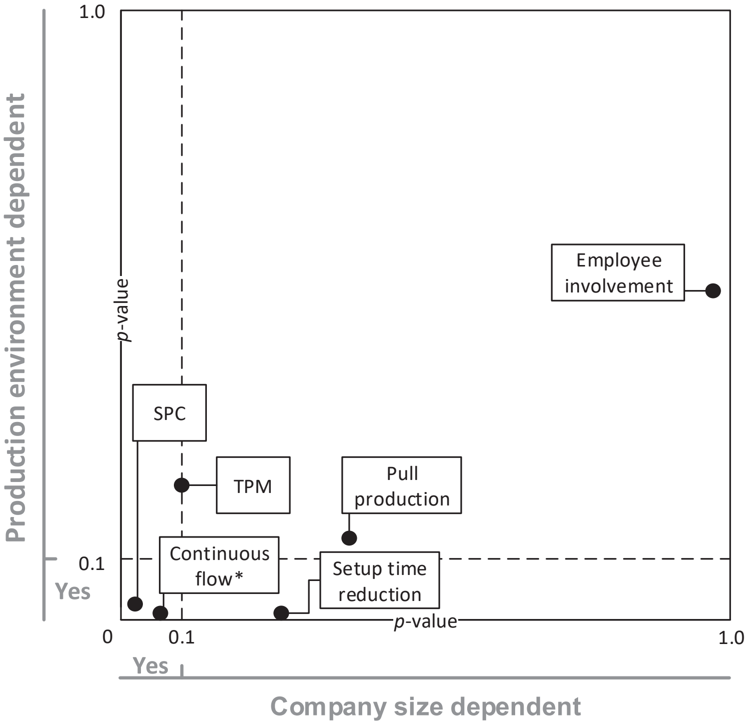


*Figure 4.5: The context-dependency of ILPs (*Continuous flow is production environment dependent for LEs and company size dependent for configure-to-order production)*

These findings support earlier studies which claim that some aspects of lean manufacturing are universally applicable, while others are most suited for environments closely resembling the automotive industry. A somewhat common perception in the industry is that “lean does not suit us.” The results show that there are examples of high adopters independent of their production environment and size, which indicates that this might be a rash conclusion. The findings presented in this paper can work as a guideline for managers in determining which ILPs are most applicable in their particular environment. However, it is important to remember that lean manufacturing should be adapted to the specific environment rather than directly copying Toyota’s formula, and that lean manufacturing does not have a defined endpoint but is a process of continuous improvement (Åhlström, 1998; Marodin and Saurin, 2013).

Limitations
This study is prone to the common limitations of survey-based research. One limitation is the sample population, which was composed solely of Norwegian manufacturers. Although we expect these results to hold for manufacturers in general, we cannot claim that this is the case. Furthermore, there might be a bias in the way that some respondents possibly overestimated their implementation level. However, as the respondents were guaranteed anonymity and would not gain anything from overestimating their results, we expect that this is not a major concern in this study. Finally, the sample size might not be large enough to uncover small effects. However, the practical significance of such small effects can be questioned.

4.4 The implementation pattern of digital technologies

Background
Digitalization is currently considered an important enabler of competitive advantage, which can be observed through the numerous government programs focused on the digitalization of industry (European Commission, 2017; Liao et al., 2017). Earlier research has emphasized the need for a “fit” between technology and the environment in which it is implemented (Congden, 2005). Although Industry 4.0 pilot projects can be observed across the industrial spectrum, the actual universality of the technologies associated with Industry 4.0 remain unclear (Sommer, 2015; Strandhagen et al., 2017). This concerns both the applicability across different production environments as well as company sizes.

Purpose
This paper aimed at uncovering differences in the level of implementation of different digitalization aspects among different types of production environments and company sizes. The focus was on three digitalization aspects: *shop floor digitalization, technologies for vertical and horizontal integration,* and *organizational IT competence.*

Findings
The data used in this study were collected through a survey of Norwegian manufacturing companies, as described in Section 3.1.2. First, based on the gathered responses, we calculated descriptive statistics, where the data were grouped based on the four different types of production environment presented in Section 2.3 (Table 4.9) and its size (Table 4.10). This provided an overview of the current digitalization status in manufacturing companies and gave indications of possible group differences. The production environment group *batch production of standardized products* had the highest mean in all three digitalization aspects, while *complex customer order production* had the lowest mean regarding shop floor digitalization and technologies for

horizontal and vertical integration. Larger companies also generally scored higher than smaller companies. However, whether these differences were statistically significant was further investigated through a two-way ANOVA.

Table 4.9: Descriptive statistics grouped by production environment

	Production environment			
	Complex customer order production (*n* = 25)	**Configure to order products (*n* = 16)**	**Batch production of standardized products (*n* = 21)**	**Repetitive mass production (*n* = 14)**
	Mean (*SD*)	**Mean (*SD*)**	**Mean (*SD*)**	**Mean (*SD*)**
Shop floor digitalization	2.54 (0.66)	2.92 (0.69)	3.02 (0.82)	2.80 (0.65)
Technologies for vertical and horizontal integration	2.82 (0.68)	2.86 (0.58)	3.08 (0.81)	2.89 (0.63)
Organizational IT competence	2.85 (0.85)	2.77 (0.87)	2.87 (0.81)	2.70 (0.57)

Table 4.10: Descriptive statistics grouped by company size

	Company size	
	SMEs (*n* = 36)	**LEs (*n* = 40)**
	Mean (*SD*)	**Mean (*SD*)**
Shop floor digitalization	2.60 (0.64)	2.99 (0.76)
Technologies for vertical and horizontal integration	2.86 (0.63)	2.96 (0.74)
Organizational IT competence	2.65 (0.79)	2.96 (0.76)

The results from the two-way ANOVA are presented in Table 4.11. This analysis showed that LEs have a significantly higher level of digitalization of the shop floor and organizational IT competence than SMEs. Regarding the difference between production environments, no statistically significant difference in the implementation level could be found. These findings indicate that a company's size is a more significant predictor of digitalization than its production environment. To summarize the results, Figure 4.6 illustrates the context-dependency of the three digitalization aspects.

Table 4.11: Results from the two-way ANOVA

		ANOVA *F*-value	Effect size[a]
Production environment	Shop floor digitalization	1.400	0.051
	Technologies for vertical and horizontal integration	0.208	0.009
	Organizational IT competence	0.114	0.005
Company size	Shop floor digitalization	5.056*	0.062
	Technologies for vertical and horizontal integration	0.182	0.003
	Organizational IT competence	2.823†	0.039
Production environment × company size	Shop floor digitalization	1.127	0.041
	Technologies for vertical and horizontal integration	0.689	0.029
	Organizational IT competence	0.508	0.021

Notes: †$p < 0.1$; *$p < 0.05$; [a]Reports eta-squared (η^2); effect sizes from eta-squared: small = 0.01–0.06, medium = 0.06–0.138, large > 0.138

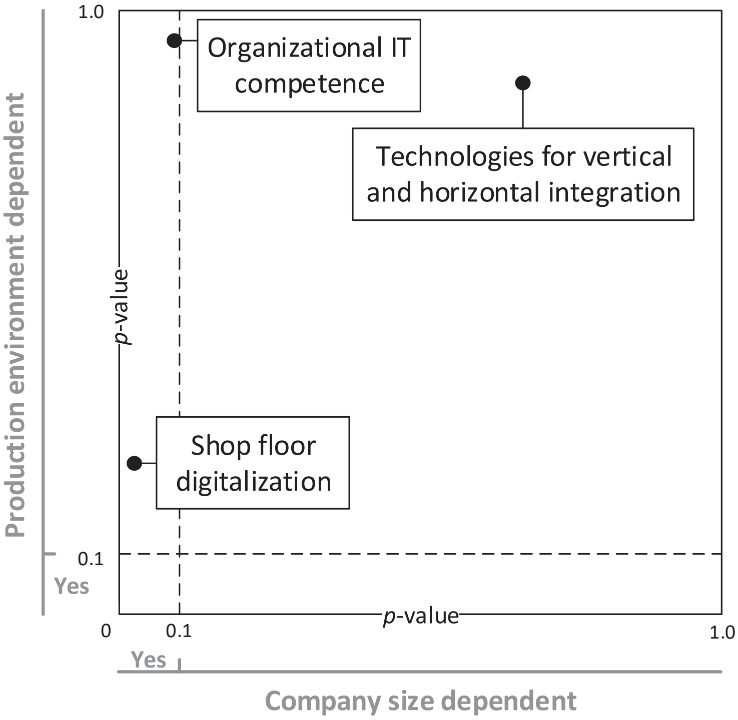


Figure 4.6: The context-dependency of digitalization

Although implementation level does not equal applicability, our findings provide insights for managers regarding which digital technologies are more applicable in which specific environments. The lack of any significant relationship between production environment and digitalization is contradictory to earlier research propositions, which predicted that the increased repetitiveness would facilitate the digitalization process. These findings thus present an important contribution to theory by suggesting that production environments might not be such a strong predictor of the implementation level of digital technologies as earlier studies have suggested. This should motivate managers to investigate the possibilities offered by emerging technologies even if their company is outside of the industrial spectrum that typically has been associated with the extensive use of AMTs and robotic systems. Earlier research has prophesied that the digitalization trend, including Industry 4.0, will only be beneficial for the LEs. This study contributes to testing this commonly held opinion and lends support to it regarding two out of the three digitalization aspects investigated. The importance of company size should, therefore, be acknowledged in similar studies in the future.

Limitations
This study is prone to the common limitations of survey-based research, similar to those described for Paper 3. Additionally, since this survey mapped the use of digital technologies, which is an emerging area, there are risks associated with the respondents not understanding the question or under- or overestimating their actual implementation level. However, the measurement instrument was developed with this in mind, and special care was taken to have clear descriptions of all questions. This should have mitigated some of this risk.

4.5 The effects on operational performance

Background
To remain competitive, the most recent trend that manufacturers have embraced is the use of a wide range of digital technologies known under the umbrella term Industry 4.0. However, few studies have investigated the actual performance implications of implementing such technologies. Further, there exists only scattered, non-conclusive research about the relationship between Industry 4.0 and the long-established lean manufacturing domain, and how they, together, influence operational performance.

Purpose
This study investigated the relationships among lean manufacturing, factory digitalization, and operational performance. In addition to investigating the main effects of lean manufacturing and factory digitalization on operational performance, their interaction effect on operational performance was also investigated. The presence of a positive interaction effect suggests a synergistic effect that is greater than the main effects of the domains combined.

Findings
This study is based on data collected from the survey described in Section 3.1.2 and presents several relevant findings. First, this study identified a strong correlation between the implementation level of lean manufacturing and factory digitalization (Table 4.12). This indicates that these two domains tend to co-exist in manufacturing companies, challenging the opinion that they are incompatible. Combining lean manufacturing and digital technologies can be an effective way to manage production, and weaknesses in one of the systems can be addressed by solutions from the other. In light of the Industry 4.0 wave, these findings indicate that it should not necessarily be the case that *either* Industry 4.0 *or* lean manufacturing is implemented but rather that these domains work together.

Table 4.12: The means, SDs, and bivariate correlations

			Correlations				
	Mean	**SD**	**1**	**2**	**3**	**4**	**5**
1. Production repetitiveness	2.31	1.13	-				
2. Company size	2.40	0.70	0.048	-			
3. Length of lean implementation	3.05	1.01	0.045	0.257*	-		
4. Lean manufacturing	3.02	0.67	0.253*	0.120	0.423***	-	
5. Factory digitalization	2.93	0.68	0.151	0.092	0.405***	0.645***	-
6. Operational performance	3.43	0.48	0.045	0.031	0.080	0.422***	0.420***

Notes: *$p < 0.05$; ***$p < 0.001$

Next, the effects of lean manufacturing and factory digitalization on operational performance were investigated through the use of hierarchical linear regression. To control for systematic biasing effects (Ketokivi and Schroeder, 2004), we decided to include three control variables in the regression: production environment, company size, and length of lean implementation. In total, three models were tested. Model 1 looked only at the effects of the control variables on the dependent variable (i.e., operational performance). Next, Model 2 added the direct effects of lean manufacturing and factory digitalization on the dependent variable. Finally, in Model 3, the interaction term (i.e., lean manufacturing × factory digitalization) was added. The results from the hierarchical linear regression analysis are presented in Table 4.13. Model 1 explains only a negligible amount of the variance in the operational performance, suggesting that factors other than the control variables are responsible for this variance. Adding the two hypothesized predictors (Model 2) and the interaction term (Model 3) produced significant improvements to the model (cf. the change in R^2). Model 2 shows significant positive relationships between both lean manufacturing and factory digitalization and operational performance. Furthermore, Model 3 shows a significant positive relationship between the interaction term and operational performance, indicating a synergistic relationship between lean manufacturing and factory digitalization.

Table 4.13: Results from the hierarchical linear regression[a]

	Dependent variable: Operational performance		
	Model 1	**Model 2**	**Model 3**
Production repetitiveness (control)	0.041	−0.074	−0.049
Company size (control)	0.009	0.014	−0.033
Length of lean implementation (control)	0.076	−0.176	−0.178
Lean manufacturing		0.326*	0.305*
Factory digitalization		0.290*	0.235†
Lean manufacturing × factory digitalization			0.247*
F-value	0.196	4.416**	4.750***
R^2	0.008	0.242	0.295
Adj. R^2	−0.034	0.188	0.233
Change in R^2		0.234***	0.053*

Notes: †<0.10; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; [a]Standardized regression coefficients are reported.

To allow for further interpretation, the interaction effect is plotted in Figure 4.7 and Figure 4.8. Based on Model 3, this is done by generating a series of simple regression equations and then calculating the predicted values of the dependent variable at high and low levels of the predictor variables (Aiken et al., 1991; Dawson, 2014). As suggested by Cohen et al. (2015), the high levels were defined as being one *SD* above the mean, while the low levels were defined as being one *SD* below the mean.

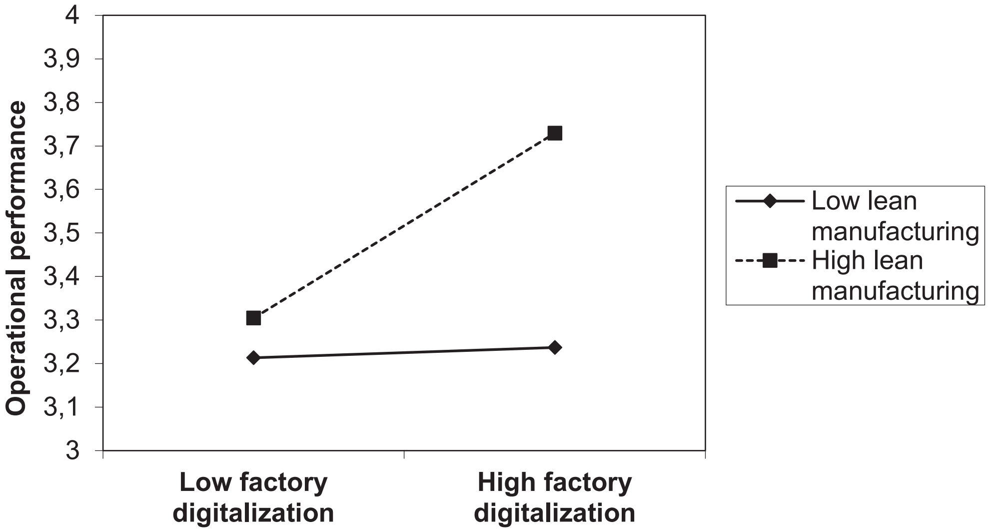


Figure 4.7: Illustration of the interaction effect between lean manufacturing and factory digitalization with lean manufacturing as the moderator

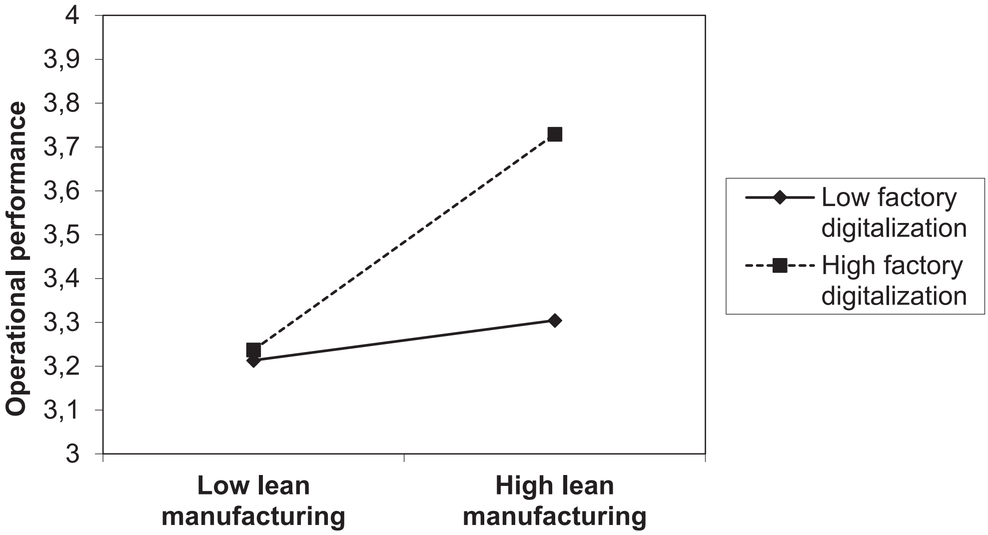


Figure 4.8: Illustration of the interaction effect between lean manufacturing and factory digitalization with factory digitalization as the moderator

The regression analysis shows that both lean manufacturing and factory digitalization individually contribute to improved operational performance. Regarding the operational performance benefits of using lean manufacturing, the findings of this study are in line with the majority of the earlier studies, confirming the positive relationship. However, different from most earlier studies, this study simultaneously investigated the use of digital technologies, a possible confounding variable. This enabled us to isolate the unique effects of lean manufacturing practices, which still exhibited significance. These findings confirm that lean manufacturing is still a relevant source of competitive advantage. Although many of the ideas and methods in lean manufacturing can be traced far back, the focus on creating value for the customer and eliminating waste are ideas that will not become obsolete, regardless of the technological advances that come about.

Investigating the relationship between emerging digital technologies and operational performance presents a novel contribution. While the potential of these technologies is widely discussed, academic studies investigating their actual impact are scarce. Contributing to the knowledge in this area, this study confirms a positive relationship between the use of such technologies and operational performance. This study thus provides evidence which suggests that emerging digital technologies support operational performance improvements and that smart and integrated production processes provide a source of competitive advantage.

The final, and arguably most important, finding of this study is the synergistic effect of lean manufacturing and factory digitalization on operational performance. The findings show that the benefits to operational performance when implementing either lean manufacturing or digital technologies in isolation are relatively modest, as illustrated in Figure 4.7 and Figure 4.8. The true operational performance advantage comes when both domains are implemented; in other words, their concurrent use produces a synergistic effect that is larger than the sum of their individual contributions. That these two domains seem to be so dependent on each other to create competitive advantage presents some interesting implications. As the companies we surveyed were asked to evaluate themselves in comparison to their competitors, this finding suggests that, to achieve superior operational performance today, an integration of these two domains is required. A basic lean manufacturing system with no digital solutions no longer provides any significant operational performance advantage. Similarly, digitalizing manufacturing operations that are not aligned with lean thinking and fail to recognize the importance of lean principles and practices is also of limited value. Earlier research has emphasized that IT resources create limited value on their own and should be used to support and enhance organizational capabilities and business processes (Liang et al., 2010). The ability to introduce digital technologies and align them with well-proven lean principles is evidently an important contributor to operational performance. In light of the upcoming fourth industrial revolution, these findings suggest that lean manufacturing is not obsolete, but rather that lean manufacturing is more important than ever to reap the benefits from digital technologies and translate them into increased operational performance.

Limitations

This study is prone to some of the common limitations of survey-based research, already presented for Papers 3 and 4. This is especially related to the sample consisting of only Norwegian manufacturers and the risk of bias in the responses.

4.6 Using digitalization for continuous improvement

Background

In contrast with the three previous industrial revolutions, Industry 4.0 is the first to be announced *a priori* (Drath and Horch, 2014). Although this provides an excellent opportunity to shape and optimize the solutions before they are fully released, the lack of empirical data makes the research highly theoretical, and there are plenty of disagreements and differences in the literature regarding what Industry 4.0 is and what it consists of (Buer et al., 2018b). Different perspectives in various studies have resulted in more than 100 different Industry 4.0 definitions available in the literature (Moeuf et al., 2018), new definitions are proposed regularly, and large differences between these can be found both in semantics and in content. This ambiguity in definitions makes it harder to align research in the area, as well as making it more complicated for practitioners to understand what Industry 4.0 entails and how to achieve this transition. The lack of a clear and agreed upon definition will lead to empirical testing of an inexact and imprecise concept, and consequently, results from empirical testing will make only marginal contributions and prevent academic progress (Meredith, 1993; Shah and Ward, 2007).

Purpose

The objective of this paper was two-fold. First, this paper aimed at clearly defining digitalization, a key enabler of Industry 4.0. Second, it aimed at providing a framework for how digitalization can be used for process improvement.

Findings

Through examining the current literature, we found three terms frequently referred to when discussing Industry 4.0 related topics: *digitization, digitalization,* and *digital transformation*. However, we observed that there were differences in opinion on how the three relate to each other and whether some are synonymous. We propose that clearly defining these terms will support further research in this field, and based on the literature findings, we suggest these definitions:

- **Digitization:** The conversion from an analog format into a digital format.
- **Digitalization:** The use of digital data and technology to automate data handling and optimize processes.
- **Digital transformation:** Creating new business opportunities through the use of digital data and technology.

Figure 4.9 further depicts the relationship among these three terms, illustrating the enabling relationships.

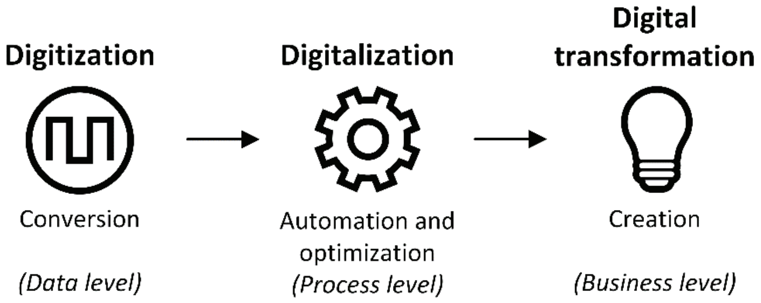


Figure 4.9: Digitization, digitalization, and digital transformation (Adapted from Maltaverne, 2017)

Next, to provide a framework for how digitalization can be used for continuous improvement, the data-driven process improvement cycle was introduced. While existing maturity models on digitalization are typically heavily focused on specific technologies, this framework instead focuses on the capabilities of the systems related to the data format and the degree of automated data handling.

The data-driven process improvement cycle consists of two parts: an improvement cycle and an associated digitalization typology. The improvement cycle (Figure 4.10) proposes that the road toward improving processes through digitalization can be broken into five steps: 1) data collection, 2) data sharing, 3) data analysis, 4) optimization, and 5) feedback. This represents the process from gathering of data until it is used to make an adjustment to the process. While these steps resemble a generic improvement cycle such as Plan – Do – Check – Act (PDCA) or Define – Measure – Analyze – Improve – Control (DMAIC), the novelty of this approach is related to the use of the associated digitalization typology (Table 4.14).

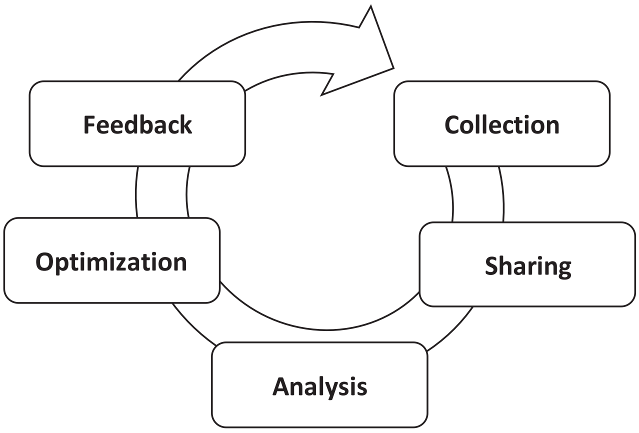
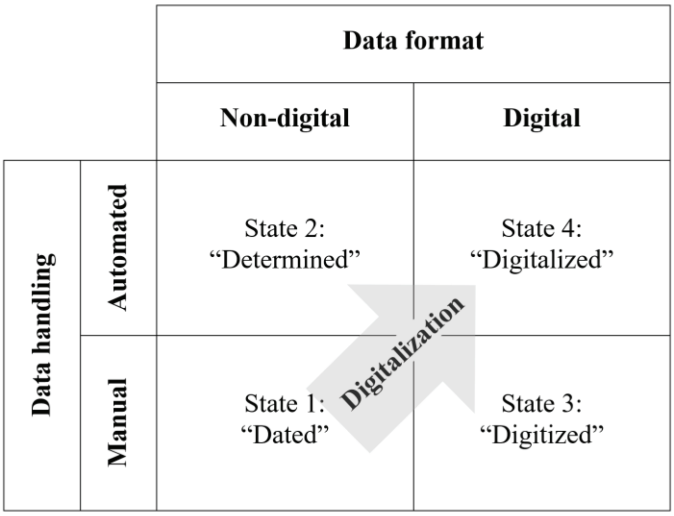


Figure 4.10: The data-driven process improvement cycle

Table 4.14: Digitalization typology



		Data format	
		Non-digital	**Digital**
Data handling	**Automated**	State 2: “Determined”	State 4: “Digitalized”
	Manual	State 1: “Dated”	State 3: “Digitized”

The digitalization typology should be used to classify each of the steps in the improvement cycle according to two dimensions: *data format* and *data handling*. The two dimensions can be summarized as a 2 × 2 matrix, as shown in Table 4.14. Each of the steps in the improvement cycle can find itself in one of these four states. *State 1* represents traditional paper-based situations, characterized by a large proportion of manual data handling. *State 2* might be effective but is inherently inflexible. *State 3* has digitized the data flow, with the obvious benefits this entails, for instance, those related to cost, time, and flexibility. However, human intervention is still needed. *State 4* represents a situation where the data is digital and handled automatically, which is a step toward enabling self-optimizing processes.

We propose that organizations will reap the greatest benefit from digitalization when all five steps in the presented improvement cycle are both digital and automatic (State 4). Processes might be partly or fully digitized, but as long as the cycle is not completed automatic, the full potential of digitalization will not yet be realized. Organizations can use the data-driven process improvement cycle as a part of their digital transformation. Three potential usage areas are outlined:

- **Mapping and measurement of digitalization levels:** The data-driven process improvement cycle presents a simple approach to measure an organization's progress toward digitalizing its processes. The method emphasizes the importance of not digitizing and digitalizing just for the sake of it, but to focus these efforts toward actually improving processes. The data-driven process improvement cycle highlights that the digitalization efforts should be directed toward the five steps essential in any continuous improvement regime.
- **Guide to prioritizing improvements:** Similar to maturity models, a process mapped according to the data-driven process improvement cycle clearly points out areas for improvement, in this case, areas for increased levels of digitalization. It thus creates a process-specific roadmap toward digitalization. Similar to PDCA, it is used for individual processes, and organizations will find it beneficial to develop an overall business framework to coordinate the individual improvement projects.
- **Plan for improvement:** An organization typically starts with an optimization goal in mind, such as increased productivity or reduced cost. The data-driven process improvement cycle provides an intuitive interface that exhibits how a system for continuous improvement of a specific variable can be designed. In these cases, the improvement cycle should be reversed, starting with specifying the optimization goals. Next, an analysis process should be designed, specifying which data need to be collected in order to facilitate improvements. The lasts steps are to plan how these data can be shared and collected.

The data-driven process improvement cycle focuses on grasping the opportunities for data-driven improvements enabled by the increasing amounts of data available from IT systems. The usage of the tools is further illustrated by presenting four scenarios from Kanban control, where each scenario is mapped according to its digitalization level. These are as follows:

- **Level 1. Traditional physical card-based Kanban:** The Kanban system traditionally relies heavily on physical cards. Although these cards are intuitive and easy to understand, there are some issues and limitations with them. The ability to handle a large number of variants, the lack of flexibility, and the risk of losing the actual cards are among the challenges faced in traditional Kanban systems (Thoben et al., 2014). In this system, in respect to the data-driven process improvement cycle, all five steps are executed manually, and the data is in a physical format. Most of the time, only the first two steps are undertaken, that is, collecting the data about materials that need replenishment, and then sharing this information with the preceding workstation. Typically, this data is only sporadically used to complete the improvement cycle by analyzing the frequency of the Kanban signals and optimizing the number of Kanban cards and bin sizes.

- **Level 2. e-Kanban:** An electronic Kanban system, known as e-Kanban, is able to meet and handle some of the challenges typically associated with physical Kanban cards (Drickhamer, 2005; Thoben et al., 2014). Transmitting the Kanban signal electronically also makes it significantly more applicable for interplant deliveries. However, even if the system is converted to a digital one, the process of transmitting Kanbans is still manual. Typically, a human worker still has to manually determine when material replenishment is needed (collection) and then send the Kanban, typically through scanning a barcode or entering it manually into the computer system (sharing). Analysis and optimization are also normally done manually.
- **Level 3. Autonomous Kanban:** Being able to automate the replenishment decision and the transmission of the Kanban signal will practically automate the Kanban loop (Hofmann and Rüsch, 2017). An industrial example of an autonomous Kanban system is the iBin system delivered by Würth presented in Kolberg et al. (2017). This bin automatically records the material level and sends it to the inventory control system. Based on this, orders are sent automatically to suppliers when needed. However, even if the Kanban loop is autonomous, it does not mean it is continuously improved automatically. The number of cards and bin sizes are still fixed, which might result in material shortages, or in the opposite case, materials might spend an excessive amount of time in intermediate inventories, halting endeavors to decrease throughput time.
- **Level 4. Self-optimizing Kanban:** Building on the autonomous Kanban system, a self-optimizing Kanban process is not only able to run the Kanban loop autonomously but also use the collected data to analyze and prioritize improvements. A self-optimizing Kanban system autonomously adjusts the bin size, as well as the number of cards in circulation, according to predefined performance objectives, such as cost, throughput time, or a similar factor.

Table 4.15 compares the four different Kanban scenarios.

Table 4.15: Comparison of the Kanban scenarios (see Table 4.14 for explanation of the different states)

	Collection	Sharing	Analysis	Optimization	Feedback
Level 1. Traditional Kanban	State 1	State 1	State 1	State 1	State 1
Level 2. e-Kanban	State 3	State 3	State 3	State 3	State 3
Level 3. Autonomous Kanban	State 4	State 4	State 3	State 3	State 3
Level 4. Self-optimizing Kanban	State 4	State 4	State 4	State 4	State 4

Limitations

The results presented in this paper are based on the literature and our own experiences. Thus, there has not been a rigorous empirical research process behind the development of the presented improvement cycle and digitalization typology. Furthermore, these tools have not been tested in empirical settings.

Digital Lean Manufacturing at Kongsberg Maritime Subsea 5

To investigate the interfaces between lean manufacturing and digital technologies in more detail, a descriptive case study was conducted. This study aimed to present four different cases where existing lean manufacturing practices have been supplemented and enhanced through the use of digital technologies. This chapter presents the findings from this descriptive case study in detail.

5.1 Overview of the case company

Kongsberg Maritime Subsea (KMS) is a subsidiary of Kongsberg Maritime which is a part of the Kongsberg Group. One of their manufacturing plants is located in Horten, Norway, which is where this case study was conducted. KMS develops and produces advanced underwater acoustic sensor systems. These products are used in underwater mapping, underwater navigation, and fishing. With manufacturing locations on three continents, in total, Kongsberg Maritime has 7,600 employees (April 1, 2019) and a yearly turnover of 7,545 MNOK (2018), while their site in Horten has approximately 450 employees. A detailed mapping of the production environment of KMS can be found in Paper 2.

KMS started its lean journey in 2014 with the establishment of the corporate lean program, “The KONGSBERG Way.” Rather than focusing on creating an implementation roadmap with detailed plans for introducing specific lean manufacturing tools, the leadership focused on building a culture for learning and continuous improvement. This culture should be embedded, they believed, all the way from the shop floor to top management. Based on its extensive lean transformation in recent years, KMS received the Norwegian Lean Enterprise of the Year award in 2017. This is a yearly accolade awarded by the knowledge-sharing platform Lean Forum Norway. An illustration of “The KONGSBERG Way” is shown in Figure 5.1.

Figure 5.1: The corporate lean program at KMS: “The KONGSBERG Way”

For KMS, the opportunities derived from digital technologies could be the next step for their lean manufacturing system. The organization has started to investigate the functionalities of these technologies and what they offer for building new capabilities for KMS. The next sections will examine some of the pilot projects in which digital technologies have been implemented in the production at KMS. Some of the cases presented are examples of technologies implemented to enhance existing lean manufacturing practices. Others might not be explicitly linked to existing lean manufacturing practices. However, common to all is that they have been implemented in line with KMS’s lean philosophy and with the aim to achieve overall lean goals, such as improved quality and reduced cost. For each case, three aspects will be discussed. First, the process “predigitalization” will be discussed, together with highlighting some of the process-related challenges that motivated the digitalization. Next, the digital solution will be described. Finally, there will be some reflections surrounding the benefits and limitations of the implemented digital solution.

5.2 Case 1: Digital TPM

KMS operates in a market segment with high quality standards, and timely and correct maintenance of the production machinery and equipment is of great importance. KMS does not have a large maintenance staff, and most of the routine maintenance is delegated to the operators. KMS previously found that most of its downtime in production was unplanned (approximately 70% of total downtime), and it was observed that the machines with the most unplanned downtime typically were those that required the most maintenance. Although KMS had implemented TPM practices in its production, KMS experienced a lack of reporting of completed maintenance tasks. It was unclear whether the lack of reporting was due to tasks not being completed, or whether the operators forgot or did not want to spend time on reporting. In an attempt to reduce the amount of unplanned downtime, KMS decided to develop a pilot project where they moved from a traditional paper-based TPM system to a digital platform.

The digital TPM platform was developed in-house based on existing functionalities in the Office 365 online platform. As this platform was already implemented in the organization, this meant no additional implementation cost except for the in-house development time. This platform supports both desktop and mobile devices. The pilot started in one department of the production, with around 20 periodic maintenance routines. After a periodic maintenance task is added to the database, the software automatically schedules the periodic maintenance task based on the service interval and notifies and delivers the work order directly to the operator. The operator receives the work order typically a few days before its due date and can sign off on a completed task. It is also possible for the operator to suggest alterations to the procedure or the service interval. Additionally, any need for unplanned maintenance can be reported directly within the system, and the appropriate personnel can be notified. After a trial period, there was an internal evaluation among the employees regarding their satisfaction with the new, digital solution. The feedback was generally positive, and it was decided to roll out this solution to the whole production process. From 20 routines in the system, KMS now has a total of 160 maintenance routines registered in the system. Currently, functionality is being added for tracking the inventory levels of spare parts and consumables. KMS has also started to investigate the potential for using IoT-based sensors for monitoring and predicting maintenance of machinery.

With the digital TPM solution implemented, a larger number of completed tasks are now registered in the system. A recent number shows that 81% of the tasks are done within the due date. As the tasks now are distributed to the individual operators, they get a notification whenever maintenance tasks are required. This might also increase the operators’ “ownership” of the tasks so that they feel more responsible in completing the task on time. It also provides managers with easy access to data about their current performance, which can be used in dashboards and as key performance indicators (KPIs).

5.3 Case 2: Digital Kaizen

KMS previously employed traditional “board” Kaizen. This means that each production area had their own analog board, where employees could post improvement suggestions. Each week, these were discussed at Kaizen meetings. However, there were some challenges with this system, especially from the production manager's point of view. Because of the large number of boards and Kaizens, it was difficult for the production manager to keep track and have an updated overview of the current improvement suggestions. This lack of an overview made it challenging to prioritize the different Kaizens and identify which were the most important ones. Additionally, as the Kaizens were only written down on a note and posted on a board, there was also a risk that these would get lost before they were handled.

Before the Kaizen system at KMS went "fully digital," there was a transition period where notes were still written on paper, but then added into the computer system. Now, Kaizens are written directly into the cloud-based system. The system is based on the same infrastructure as the digital TPM system, Office 365. The physical boards have been replaced by screens which show the digital Kaizen board. There are different boards for different areas, but notes can easily be transferred between boards. There is also the possibility to tag the different Kaizens, which supports the prioritization process. For instance, health, safety, and environment (HSE)-related issues are the top priority at KMS, and implementing Kaizens related to this are thus prioritized. Even if the Kaizen system now is digital, KMS still sees the value of having meetings around the screens showing the virtual boards. They see that this kind of group discussion is essential to promote problem-solving, creativity, and innovation.

With the digital Kaizen solution, it is easier for managers and team leaders to get an overview. It enables efficient prioritization of improvement suggestions and a "to the point" Gemba walk.[1] It also simplifies and automates tracking of KPIs, such as the number of monthly Kaizens and the processing times of individual Kaizens. The production manager considers the digitalization of the Kaizen system essential for the survival of the Kaizen culture at KMS. The large number of improvement suggestions in analog format led to difficulties for the production manager to handle them properly. If this trend had continued, it was likely that the enthusiasm for Kaizen would have diminished. Now, digital technologies help managers and team leaders to sort, organize, and visualize so that less time is needed to prepare for Kaizen meetings. Since the individual Kaizens can be tracked, it enables greater transparency for the workers so they know their suggestions are actually seen, considered, and handled. This is likely a motivating factor to maintain enthusiasm about Kaizen at KMS.

5.4 Case 3: QR-Kanban

In addition to the materials that are used directly in the products, KMS also has a significant consumption of different types of consumables, such as gloves, lubricants, and cleaning solvents. Previously, with no standardized routines, the person responsible for ordering had to manually write an e-mail to the right supplier with the right product ID and the appropriate quantity each time additional goods were needed. This low level of standardization led to excessive work, and the possibility to introduce a Kanban solution was investigated.

The introduction of Kanban cards was deemed appropriate to standardize the ordering of consumables. However, as ordering still was conducted through e-mails, quick response (QR) codes were printed on the Kanban cards. QR codes are two-dimensional barcodes, which can

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[1] *Gemba* is a Japanese term meaning "the actual place." In a business context, it refers to the place where value is created. Gemba walks thus refer to the action of going to see the actual process. Through observing and asking questions, managers can obtain a greater understanding of the value stream.

store more data than traditional barcodes. The exact amount depends on the resolution of the QR code. This means that the entire ordering e-mail can be stored within the barcode. As a result, the ordering process is decentralized without the need to communicate with a central database, which is typically the case with traditional barcodes.

The Kanban card with a QR code enables simple ordering of products via mobile devices with a camera. It has standardized the ordering process between KMS and its suppliers of consumables, simplifying the process for both parties. The fact that the card never has to leave the inventory location reduces the risk that the card gets lost, a challenge faced in traditional Kanban systems. Although it is a less advanced solution than the autonomous Kanban systems that are starting to emerge, this solution was deemed sufficient since these products are ordered less frequently, and the implementation cost was next to nothing.

5.5 Case 4: 3D-printing of casting molds

The casting of composites is an integral part of the production process at KMS. With a total of 28 different composite types and up to 100 units produced per week for the high runners, a large number of casting molds are required. Traditionally, KMS used Teflon-based casting molds. While these can be used multiple times, they need careful cleaning after each use. KMS estimated that 700 man-hours are spent each year cleaning these molds. The cleaning also wears out the molds, which can lead to erroneous dimensions of the product. Additionally, the Teflon-based molds are bulky and require significant storage space, and operators are exposed to heavy lifting when moving the molds.

As a response to these observed challenges, two years ago, KMS started to 3D print their own casting molds made of plastic for one-time use. During initial testing, they observed that the 3D-printed molds produced similar results as the traditional molds while mitigating the challenges outlined above. As the 3D-printed molds keep getting verified based on KMS's strict quality requirements, they are used on an increasing number of composite types. Using fused deposition modeling (FDM), molds are produced as they are needed, typically the week before they are supposed to be used for the casting process.

Initial testing of the 3D-printed casting molds indicated several advantages compared to the traditional method. First, there are significant cost savings regarding both the direct cost of the molds and indirect cost of cleaning the molds after use. So far, even if they only have implemented it on 6 of 28 composite types, the savings related to mold cost and cleaning cost amount to around €50,000 per year. Since the need for mold cleaning is eliminated, the setup time is drastically reduced. As the molds are produced on demand, there is also a significant reduction in the required storage capacity for molds. In the case of situations where improvements to the mold design are discovered, it is easy to adjust the design of the molds, and the changes can be implemented immediately. Finally, the 3D-printed molds are considerably lighter than the traditional molds, leading to improvements regarding the HSE aspects of the operation. As an area for further development, KMS is looking into how the material from the 3D-printed mold can be recycled to improve the environmental sustainability of this operation.

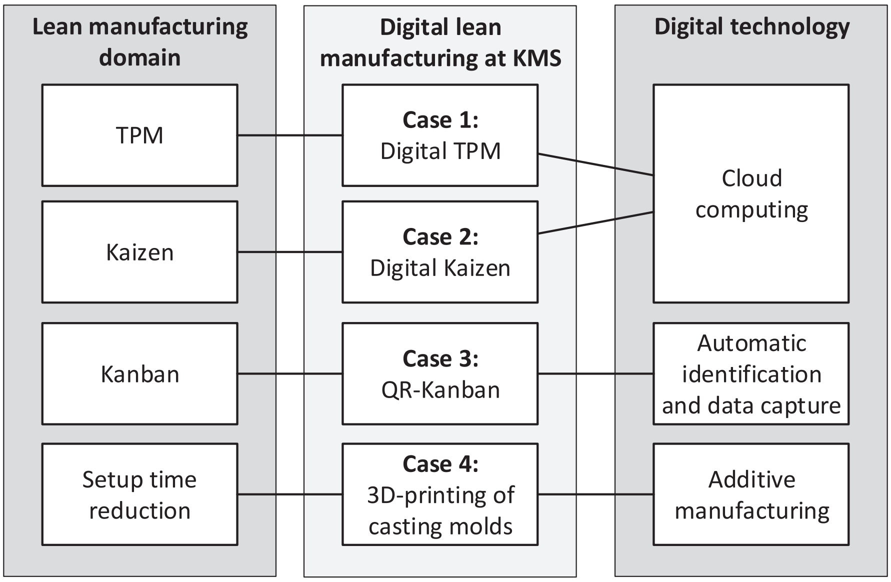

Figure 5.2: Illustration of the cases presented in this chapter, highlighting their linkages to the lean manufacturing domain and corresponding digital technologies

5.6 Concluding remarks

This chapter has presented several cases from practice on how lean manufacturing and digital technologies have been integrated. An illustrative summary of the different cases is presented in Figure 5.2. The lean program manager at KMS holds the clear position that, despite the increasing hype surrounding Industry 4.0 and related technologies, KMS will not rush into the implementation of such technologies. Technology should be implemented to handle a specific challenge, not be implemented just for the sake of it. There should also be a clear understanding of the functionalities of the technologies and what they can offer before investments are made. The lean program manager suggests following the PDCA method when implementing new technologies. First, a pilot should be developed to test the technology on a small scale. This test should confirm that the technology actually handles the challenge that was the motivation behind implementing the technology. Reflections should also be made at this stage. What did we learn from this, and how can it be improved further? If the pilot was considered successful, the learning points should be implemented, and the implementation can be extended to other parts of the organization.

Another central question is the role of the human in Industry 4.0. In the pilot projects implemented at KMS, the human is still in the center and essential for the process. Technology has not replaced the humans, but is rather supporting humans in organizing and visualizing information and carrying out some of the more repetitive and dull tasks. Furthermore, humans that are able to think critically about the work process and how to continuously improve it will be essential also in the future. While developments such as machine learning indeed enable technologies to continuously improve, they do not ask critical questions such as whether this process is the appropriate one or whether it is actually needed.

In respect to the “lean pyramid” introduced in Figure 2.5, the lean program manager predicts that the overall objectives and principles of lean manufacturing will remain the same in the future. It is rather how we operationalize lean manufacturing through tools that will change. Existing lean manufacturing tools will change, and new tools will likely be added to the lean manufacturing toolbox as technologies bring along solutions that are in line with lean principles and support the overall objectives of lean manufacturing.

Discussion 6

This chapter discusses the results of this thesis. The first section focuses on addressing the research questions, together with some short reflections on possible underlying factors that might explain these findings. Next, some general recommendations are presented regarding how lean manufacturing and Industry 4.0 should be approached. Finally, the thesis' contributions to theory and practice are highlighted.

6.1 Revisiting the research questions

6.1.1 Implementation patterns of lean manufacturing and of digital technologies

The first research question aimed at investigating the context-dependency of lean manufacturing and digital technologies:

RQ1: *What are the implementation patterns of both lean manufacturing and digital technologies across different production environments?*

In order to answer this research question, we conducted a survey to investigate the relationships between environmental factors (i.e., production environment and company size) and the implementation levels of both lean manufacturing and digitalization aspects. These results are presented in Papers 3 and 4. Based on these results, we can summarize the findings related to *RQ1* as follows:

Main findings: *The implementation levels of lean manufacturing and digital technologies tend to be highly correlated and have similar implementation patterns. Both domains have the highest implementation level in production environments resembling batch production of standardized products, while the implementation levels are typically lowest in production environments characterized by complex, one-of-a-kind production. If the production environments are sorted according to their degree of repetitiveness, the implementation level follows an inverted U-shaped curve. Company size is a significant predictor for the implementation level of two of the three investigated aspects of digitalization, but not for lean manufacturing.*

Papers 3 and 4 go further into discussing the underlying factors that may explain these findings. Regarding the implementation patterns across different production environments, the results for lean manufacturing were as expected based on the literature. There are complicating factors on both ends of the production repetitiveness "scale" that influence the applicability of lean manufacturing practices. Although studies have investigated the relationship between the type of production environment and lean manufacturing implementations in the past, the methodological contribution of our study is a more detailed grouping of production environments. While most earlier studies treated production environment as a variable with two categories, our study used four different categories. This way, we obtained more nuanced results regarding the implementation level of lean manufacturing across different production environments. As a result of this methodological choice, we could clearly see that the relationship resembled an inverted U-shape with lower levels of implementation at the two extremes of the repetitiveness scale. Testing it statistically, a quadratic regression model had the best fit with the data and was statistically significant, confirming the presence of an inverted U-shaped curve. This suggests that the implementation level of lean manufacturing tends to increase with the production repetitiveness up to a certain point after which it starts to decrease. The turning point seems to be close to the level of repetitiveness where lean manufacturing was initially developed. Although the inverted U-shaped curve reflects the implementation level, we argue that it also gives a good indication of the actual applicability of lean manufacturing.

Interestingly, when merging the different digitalization aspects investigated into a single variable, the implementation pattern across production environments was similar to that of lean manufacturing. An earlier study by Strandhagen et al. (2017) suggested that there is a linear relationship between the applicability of digital technologies and production repetitiveness. Based on the mean values of the different production environments, our findings indicate that this relationship rather resembles an inverted U-shaped curve, with lower implementation levels at each end of the repetitiveness scale. However, we have some ideas regarding how this finding might be explained. First, Kagermann et al. (2013) outlined *smart factories* and *smart products* as key enablers of Industry 4.0. Regarding smart factories, the low repetitiveness in complex, one-of-a-kind production environments complicates the transition toward smart production processes in a smart factory. This could be a reason for the lower levels of implementation in highly non-repetitive environments. When it comes to the use of smart products, highly repetitive production environments typically produce commodity products where the product price is a significant order winner. Making these products “smart” might thus be considered too large of an investment compared with the value of the product. Companies in this environment also tend to have been highly automated and integrated for some time already and might not necessarily be that interested in the developments branded under Industry 4.0. Second, as we observed in the analyses presented in Paper 5, digitalization is highly correlated with lean manufacturing practices. Earlier studies have proposed that lean manufacturing is an ideal foundation for digitalization efforts (e.g., von Haartman et al., 2016), and the implementation pattern of lean manufacturing could thus be another explanation for the observed implementation pattern of digital technologies.

Early studies investigating the relationship between company size and lean manufacturing suggested that LEs to a larger degree have implemented lean manufacturing. Our study provides updated findings, which suggest that the differences between SMEs and LEs are negligible. This development reflects the increased diffusion of lean manufacturing concepts, for instance, through knowledge-sharing platforms, industrial research projects, and education. Most of the ILPs are inexpensive to implement and maintain, which supports the argument that also SMEs can easily implement these.

The implementation level of digital technologies on the shop floor, on the other hand, is found to be dependent on company size. Whereas SMEs seem to have the required knowledge and financial power to implement lean manufacturing, these still seem to be major barriers to digitalization efforts. Investing in emerging technologies requires considerable financial resources and close collaboration with hardware and software vendors. It also adds to the requirements for IT competence in the organization for implementing, maintaining, and using the new solutions. However, observing the correlation between lean manufacturing and digitalization, SMEs might find it beneficial to use their lean manufacturing system as a foundation for their transition toward Industry 4.0. We also expect that the gap between SMEs and LEs will close over time as solutions reflecting the needs and financial constraints of SMEs are developed.

6.1.2 Performance implications of using lean manufacturing and digital technologies

The second research question targeted investigating the impact on performance from lean manufacturing and digital technologies.

RQ2: *What are the performance implications of a concurrent use of lean manufacturing and digital technologies?*

To address this research question, we used survey data to analyze the relationship between the implementation levels of lean manufacturing and factory digitalization and the corresponding operational performance. The method and results are presented in detail in Paper 5. Based on this, we can summarize the findings related to *RQ2* as follows:

Main findings: *Both lean manufacturing and factory digitalization are sources of competitive operational performance. However, implementing one of these domains in isolation seems only to result in minor improvements in operational performance. The largest operational performance benefits are observed when both domains are implemented and used concurrently, resulting in a synergistic effect on operational performance levels.*

That there are limited benefits of using lean manufacturing and factory digitalization in isolation provides interesting insights. With Industry 4.0 and digitalization hailed as the next source of productivity improvement, these findings suggest that companies cannot necessarily expect the immediate adoption of Industry 4.0 to automatically result in substantial performance improvement. Industry 4.0 should be supported by a compatible management framework, such as lean manufacturing. Furthermore, these findings motivate further research on the aspects investigated in *RQ3*.

6.1.3 Digital technologies supporting lean manufacturing

The final research question aimed at exploring potential interfaces between digital technologies and lean manufacturing.

RQ3: *How can digital technologies be used to support lean manufacturing?*

To address this research question, we used existing literature, conceptual development, and a case study to highlight examples where digital technologies associated with Industry 4.0 can be or have been used to support existing lean manufacturing practices. Based on this, we can summarize the main findings related to *RQ3*:

Main findings: *Lean manufacturing practices remain a highly relevant and appropriate methodology for organizing manufacturing operations. The rapid developments in IT, especially regarding sensoring, interconnectivity, and data analytics, provide numerous opportunities to enhance existing lean manufacturing practices, ultimately increasing their applicability and leading to higher operational performance.*

This research question looked at the supportive functions of digital technologies for different aspects of lean manufacturing. Since the start of this PhD study until now, this is probably the topic that has been most discussed in research related to the integration of lean manufacturing and Industry 4.0. Especially in the last three years, numerous papers have provided different examples on possible "combinations" (e.g., Dombrowski and Richter, 2018; Powell et al., 2018; Satoglu et al., 2018). Papers typically present a number of possible scenarios (often in the form of a matrix) without going into detail on how it is done (e.g., Sanders et al., 2017; Wagner et al., 2017; Dombrowski and Richter, 2018; Mayr et al., 2018; Satoglu et al., 2018; Slim et al., 2018) or providing a specific scenario with more detailed descriptions and assessments (e.g., Hofmann and Rüsch, 2017; Meudt et al., 2017; Powell et al., 2018). However, most of these studies are conceptual. We want to emphasize the need for more empirical-based studies in this area to ensure relevance for practitioners.

The case study at KMS introduced four implemented cases with proven benefits. While the solutions implemented at KMS might not be as advanced as those that are typically advertised together with Industry 4.0, they are inexpensive, developed in-house, and focus on handling specific challenges observed in their manufacturing system. They are examples of excellent entry-level solutions for building up the digital capabilities of a manufacturing organization. These can be used as a motivation for further probing into the implementation of digital technologies, especially for SMEs.

There is no doubt that there are plenty of promising areas where digital technologies and lean manufacturing practices can be integrated. Increased data gathering, integration, and automated data analytics can enable data-driven, self-optimizing lean manufacturing tools. These developments will increasingly detach humans from operating the lean manufacturing system. However, an important issue not explicitly explored in this thesis is the appropriate level of human involvement. As discussed in Chapter 5, at KMS, they focus on keeping the human central in the process and using digital technologies only to support the operation. Digital technologies are, for instance, used to reduce time spent on repetitive tasks as well as to sort, organize, and visualize the data to support decision-making. While the ultimate goal of Industry 4.0 is a completely autonomous factory with no human operators, there is still a transition period before that goal is reached. In this period, we will see that the proportion of robots compared to human operators will increase. Thus, the interaction between robots and humans will be an important research area in the coming years.

6.2 General discussion

So how should companies approach lean manufacturing and Industry 4.0? Following a three-year inquiry into this topic, a few recommendations can be offered.

First, we would like to repeat that both lean manufacturing and digital technologies, and especially together, are associated with improved operational performance. Our findings indicate this to be valid regardless of production environment and company size. As operational performance is a critical aspect of staying competitive for manufacturing companies, we argue that this finding should be a prime motivation to seek the opportunities offered by these two domains. However, to implement either of these domains can be challenging as no standard solution exists. The implementation approach will depend on the characteristics of the production environment. Our investigation uncovered that especially environments that have a very low or very high degree of repetitiveness had not implemented lean manufacturing to the same degree as other production environments.

There are research streams dedicated to making lean manufacturing more applicable in both non-repetitive environments (e.g., Lane, 2007; Duggan, 2013) and process industries (e.g., King, 2009). These environments will not benefit from copying Toyota's recipe directly but need to transform the overall lean objectives and principles into tools that fit their environment. This is one of the reasons why we decided to use lean manufacturing practices as the unit of analysis in this study: it is a trade-off between the overall lean objectives, which are difficult to operationalize and measure, and the specific lean manufacturing tools originating from automotive industries, which are arguably best suited to similar environments. Motivated by the improved operational performance associated with lean manufacturing implementations, environments with a lower level of lean implementation should closely follow the developments that are aiming toward making lean manufacturing applicable in these environments. While new methods are proposed regularly, we also expect that emerging digital technologies can be a catalyst for widening the applicability of lean manufacturing. Paper 3 has presented a list of production environment-related factors that can complicate lean manufacturing implementations. Digital technologies provide opportunities to mitigate some of these factors. For instance, mobile robots can enable a dynamic factory layout, allowing layout changes based on operational requirements (Giordani et al., 2013). Flexible manufacturing systems can reduce changeover times and facilitate one-piece flow in environments where they were not previously considered applicable. Moreover, big data analytics enables advanced forecasting, which can support the levelling of the production schedules. Electronic Kanban systems eliminate physical Kanban cards, which extends the applicability of Kanban to environments with a large number of variants (Houti et al., 2017).

Although the difference was not statistically significant, non-repetitive environments seem to have the lowest implementation level of digital technologies. Nevertheless, we believe that it is actually these environments that will have the most substantial benefits of successfully implementing such technologies. The reasoning behind this proposition is based on the high complexity inherent in these types of environments (Bertrand and Muntslag, 1993). While lean manufacturing can be seen as a method for reducing complexity, IT provides excellent tools for managing complexity (Rauch et al., 2018). Non-repetitive manufacturers might only reduce their complexity through standardization to a certain point before sacrificing their competitive advantage. It is proposed that many of the challenges faced today by non-repetitive manufacturers, for instance, related to information sharing, localization of resources, work task complexity, and material handling, can be mitigated through a successful implementation of digital technologies (Strandhagen et al., 2019). So, our finding that the use of digital technologies seems to be somewhat lower in these environments should not be understood as a notion that these technologies are irrelevant for these environments, but rather that more research is needed to ensure a successful implementation.

Highly repetitive environments typically have streamlined production lines which are able to produce rapidly in large volumes. However, even if digital technologies will most likely not have a large direct impact on the production output for these environments, digital technologies can provide opportunities both in support functions, as well as in the design of the production system. One example could be predictive maintenance, as machine breakdowns typically have severe consequences in these environments. While highly efficient, the equipment and machinery used in these environments typically have low flexibility. Relating back to the market trend of increased individualization of products, this trend might also impact the operations of these environments, resulting in a need to offer a larger variety of products. Digital technologies can provide solutions for this.

Nevertheless, we argue that most manufacturing companies do not have to be a *leader* in the development and use of digital technologies for manufacturing unless IT is the core of the company's operations. Most manufacturing companies should rather take a *follower* stance. The advantage of being a follower is reduced risk and uncertainty, as well as the possibility to learn from the leaders. The Industry 4.0 concept is still in the maturing phase, and the greatest benefits probably still lie in the future. Much research remains to be done on how to grasp these benefits.

We find that the tool presented in Paper 6, the data-driven process improvement cycle, could be a useful framework for companies looking toward enhancing their existing processes through the use of data-driven methods. For companies with limited data collection, it can provide guidance regarding which specific data need to be collected, which again can be used to develop an infrastructure to collect and analyze these data. This could be especially useful for SMEs, whose limited financial resources force organizations to pragmatically evaluate which data to collect. It is thus a "pull" way of thinking, asking for specific data, rather than a "push," where you try to find improvement opportunities from whatever data are supplied.

This thesis has extensively discussed the interface between lean manufacturing and digital technologies. Discussing the interface, we have mainly focused on how emerging digital technologies can enhance existing lean manufacturing practices. However, other aspects of this interface should also be discussed. A central question will, of course, be whether we will still be talking about lean manufacturing in 20 years. If so, how will it be operationalized? We predict that the overall objectives of lean will be just as important in the future. New solutions will be developed to achieve these objectives. This means that the lean manufacturing tools we know today will change, and new ones will be added. As the lean toolbox grows larger, does it still make sense to talk about lean manufacturing practices and tools? What is the deciding factor to be considered a lean manufacturing tool? If it is in line with lean principles and supports achieving the lean objectives, should that not be enough to be considered a lean manufacturing tool? While this thesis has focused on lean manufacturing practices, being too focused on existing practices and tools going into a paradigm-changing era might be counterproductive. While lean manufacturing practices and tools provide a framework for how digital technologies can be utilized for specific means, it might be inhibiting significant breakthroughs. Looking at the future opportunities through "lean glasses" traceable back to the 1940s may be an inhibitor of true innovations in the way we manufacture.

6.3 Contributions to theory

Through a rigorous research process that addressed relevant gaps in current theory, this thesis presents several theoretical contributions. This section highlights these contributions to theory and further discusses their implications. Table 6.1 presents an overview of the key contributions from the six appended papers.

Table 6.1: An overview of the key theoretical contributions

	Paper					
Key contribution	**1**	**2**	**3**	**4**	**5**	**6**
A framework for mapping different production environments		X				
Highlighting the implementation patterns of lean manufacturing practices across different production environments			X			
Highlighting the implementation patterns of digital technologies across different production environments				X		
Providing empirical support for the main effects of lean manufacturing and factory digitalization on operational performance					X	
Providing empirical support for a complementary effect of lean manufacturing and factory digitalization on operational performance					X	
Presentation of concepts of how digital technologies can support lean manufacturing practices	X					X
The data-driven process improvement cycle for mapping current digitalization levels, as well as planning and guiding improvement processes						X
A research agenda for future research on Industry 4.0 and lean manufacturing	X					

The first contribution of this thesis is the integrated framework for mapping different production environments. It contributes to the contingency research of operations management, a research area that has been getting increasingly more attention (Sousa and Voss, 2008). It differs from earlier mapping frameworks in the way that it considers more variables, and the defined values for each variable make it more accessible and easy to use. We suggest that this is, among others, an excellent tool for comparison in multiple case studies where it is expected that environmental factors may influence the results and should be controlled for.

Second, Paper 3 provided new insights into the implementation patterns of lean manufacturing practices. Although this issue has been investigated in the past, our study is novel both in research design (a larger number of production environments) and findings. Previously, there have been extensive research efforts into how lean manufacturing can also be applied outside of its original automotive manufacturing context. These results provide updated findings that can help us understand which lean manufacturing practices are universal and which are context-dependent.

Third, in Paper 4, we investigated the implementation patterns of different aspects of digitalization across the same types of production environments. There has been limited research investigating how environmental factors influence the implementation levels of emerging digital technologies. These findings provide insight into the current implementation patterns. Knowing the nature of these patterns is important to guide future research efforts. This includes both research efforts to assist environments that are currently lagging behind in their digital transformation and to develop implementation frameworks that take into account the characteristics of different production environments.

Fourth, in Paper 5, we provided empirical results which show that both lean manufacturing and factory digitalization individually are related to improved operational performance. Investigating both simultaneously adds the additional methodological benefit of controlling for potential confounding effects. While much has been said and praised about the potential of the emerging digital technologies, few academic studies have investigated the performance impacts on a larger scale. Confirming the positive relationship between factory digitalization and operational performance is thus an important contribution to theory.

Fifth, Paper 5 also outlined the complementary effect of lean manufacturing and factory digitalization on operational performance. This finding presents an important contribution to theory and should motivate future research on how to benefit from lean manufacturing and digital technologies in practice.

Sixth, we have presented a number of concepts and cases for how emerging digital technologies can support lean manufacturing practices. Further, we have provided assessments on the benefits and drawbacks of such solutions, how they can address known limitations in existing lean manufacturing practices, and how they can possibly contribute to improved operational performance. These findings thus contribute to the stream of research within Industry 4.0 and lean manufacturing focusing on the supportive effects of digital technologies on lean manufacturing (Buer et al., 2018b).

Seventh, in Paper 6, we presented the data-driven process improvement cycle. In addition to clarifying some definitions surrounding the digitalization domain, it provides a structured method to map existing processes and identify possibilities for further digitalization.

The final key contribution we want to highlight is the presentation of existing research and the research agenda presented in Paper 1. This synthesis of existing research both provides an introduction to the current research frontier and highlights the current gaps in research that should be considered in future studies.

6.4 Implications for practitioners

Theoretical contributions aside, the findings of this research study should also have practical relevance for practitioners interested in applying lean manufacturing and/or Industry 4.0.

Industry 4.0 is currently being hailed as the next industrial revolution, and managers follow this trend closely. However, reaching the vision described in Industry 4.0 is not a straightforward task. This thesis presents new knowledge and frameworks that are of relevance for practitioners aiming to move their operations toward Industry 4.0, with a focus on how it relates to lean manufacturing. In an increasingly competitive manufacturing sector, the findings in this thesis thus provide valuable insights, as being able to develop production systems tailored to and reflecting the requirements of each unique production environment is an important competitive advantage.

A number of valuable insights should guide managers in their approach to Industry 4.0. The first part of this research examined the implementation patterns of lean manufacturing and digital technologies. Although implementation level does not equal applicability, the findings give indications for managers regarding which aspects of lean manufacturing and digital technologies are more applicable in which specific environments. These insights should be used by managers to adjust their targets, expectations, and approaches when implementing new improvement programs or technologies. The findings of this study also challenge the opinion that lean manufacturing and IT are incompatible. They rather show that they tend to co-exist and mutually reinforce each other. To achieve the greatest performance benefits, lean manufacturing and digital technologies should be used concurrently. This provides valuable insights when developing roadmaps for production improvement initiatives. With promises of substantial performance improvements following an Industry 4.0 implementation, there might be the temptation to focus all attention on Industry 4.0 at the expense of lean manufacturing. However, our findings indicate that existing lean manufacturing systems should not be neglected but should be used instead as a basis for deploying emerging digital technologies into the manufacturing system. For managers who are yet to explore lean manufacturing, this study provides motivation by highlighting why it can be a good idea to supplement digitalization efforts with a lean manufacturing system.

This thesis presents different examples of how lean manufacturing and digital technologies can be integrated. The examples from KMS presented in Chapter 5 focus on handling specific limitations and challenges of the manufacturing process and the related lean manufacturing practices. Although these examples are not as advanced as some of the solutions typically prophesied in the Industry 4.0 literature, they are examples of digitalization processes that promote continuous improvement of the existing system rather than digitalizing simply for the sake of it. On the other hand, the self-optimizing Kanban system presented in Paper 6 is an example of how more advanced technologies can be used to ensure data-driven continuous improvement.

This thesis also presents several frameworks which should be useful also for managers. Managers can use the framework for mapping production environments presented in Paper 2 as a starting point for designing appropriate production planning and control solutions, comparing their operations with other companies, and identifying possible improvement areas. The data-driven process improvement cycle presented in Paper 6 can be used to map the digitalization degree of current processes and provide guidance for how it can be further improved.

Conclusion 7

This chapter marks the end of this thesis by first presenting a short summary of the results together with some concluding remarks. Next, the limitations of the research are highlighted before concluding the thesis with some proposals for further work.

7.1 Summary and concluding remarks

In this thesis, the relationship between lean manufacturing and Industry 4.0 has been thoroughly investigated. This has been done through different research approaches, such as a systematic literature review, a survey, and case research. Lean manufacturing and Industry 4.0 have been investigated individually, as well as together. The key contributions provided by this thesis can be summarized as follows:

- A framework for mapping different production environments,
- New knowledge on the implementation patterns of lean manufacturing practices and digital technologies across different production environments and company sizes,
- Providing empirical support for the main and complementary effects of lean manufacturing and digital technologies on operational performance,
- Presentation of concepts and cases of how digital technologies can support lean manufacturing practices,
- The data-driven process improvement cycle for mapping current digitalization levels, as well as planning and guiding improvement processes, and
- A research agenda for future research on Industry 4.0 and lean manufacturing.

What is the future of lean manufacturing? As researchers, we cannot claim for certain what will happen, but only make predictions based on observations from the past and present. While lean manufacturing probably already has passed its hype peak, the Industry 4.0 hype might continue to grow. Observing that Industry 4.0 is being hailed as the next leap in productivity increase and that both manufacturing and consultancy firms are exchanging their lean implementation programs for digitalization programs, important reflections should be made. Amara's law states that "we tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run" (Ratcliffe, 2018). This observation might also be accurate for improvement programs. The findings in this thesis suggest that manufacturing companies who are yet to implement lean manufacturing should carefully consider whether a move toward Industry 4.0 should be their next step. Our findings indicate that a digitalized manufacturing system without complementary lean manufacturing practices experiences only minor improvements in operational performance.

7.2 Research limitations

No research is without flaws, and this section will highlight the known limitations of the research presented in this thesis.

First, the sample is composed solely of Norwegian manufacturing companies. Although we expect that these results also hold for manufacturers in general, we cannot guarantee that. Second, when using self-administered questionnaires to gather data, there is a risk that the respondents do not fully understand the questions or that there is a bias in their responses. This could be, for instance, because they under- or overestimate their implementation level or operational performance. Although we put in place some preventive measures to avoid this, for instance, guaranteeing the anonymity of the respondents and clear descriptions of the questions and alternatives, this limitation should be kept in mind. Third, the sample size of this study is smaller than some of the prominent studies in this field. However, this should be seen in the light of the manufacturing landscape in Norway, which presents difficulties in gathering large samples. Although the current sample sizes might not be large enough to uncover small effects, the practical significance of such small effects can be questioned. Finally, it is important to emphasize that, while the findings in this paper prove significant relationships among the studied variables, this does not necessarily imply causality.

The proposed frameworks (in Papers 2 and 6) have not yet been fully tested. The development of such frameworks should be seen as an iterative process where experiences gathered during the use phase should be used to improve the framework's accuracy and usability.

7.3 Future research

Future research should continue to investigate how technology affects lean organizations and how lean manufacturing implementation frameworks should be adjusted in light of the new possibilities introduced by emerging digital technologies. Due to the dynamic nature of IT and the fact that the perception of what Industry 4.0 and digitalization actually are might change over time, we emphasize the value of follow-up studies to investigate whether the relationships described in this study will change over time. The measurement instruments used in this study reflect the current state of the art in the industry but will most probably change in the coming years.

That this study confirms that both lean manufacturing and factory digitalization are positively related to operational performance should motivate further studies into how to successfully implement these domains in practice. This includes several aspects. The research agenda presented in Paper 1 highlights several promising research areas that deserve future research. While this thesis and other recently published studies have investigated some of these areas, others remain mostly unanswered.

First, research should continue to investigate the impact Industry 4.0 will have on the soft practices and human aspects of lean manufacturing. Second, studies have indicated that an established lean manufacturing system is an ideal foundation on which to build an Industry 4.0 implementation. However, research remains to determine how this should be done in practice. Related to this, we could not yet identify an implementation framework for moving toward an Industry 4.0 and lean manufacturing integration. As research on this topic matures, establishing an implementation framework should be a natural step to synthesize existing research and make it relevant for practitioners. Third, we call for descriptive studies on how both lean manufacturing and digital technologies can best be applied in different production environments with different requirements. Finally, we see that SMEs seem to lag behind the LEs in their digitalization efforts. Future research efforts should investigate how digitalization also can benefit this group of companies, which represents 99% of all businesses in the EU (European Commission, 2008).

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Appendix A: Survey Items

Part 1: Company background

Item	Alternatives
Company name	(*)
Job title	(*)
Sector/Type of industry	(*)
Firm size (No. of employees)	*1) <50* *2) 51–250* *3) >250*
Annual turnover	*1) <€10M* *2) €10–€50M* *3) >€50M*
Production environment (choose the closest fit)	*1) Complex customer order production* *2) Configure-to-order production* *3) Batch production of standardized products* *4) Repetitive mass production*
Number of years since starting lean implementation	*1) N/A* *2) <1 year* *3) 1–5 years* *4) >5 years*

(*) Open-ended question

Part 2: Mapping of lean manufacturing practices

Please indicate the extent of implementation of each of the following practices in your plant. *(1) no implementation; (2) little implementation; (3) some implementation; (4) extensive implementation; (5) complete implementation.*

Lean manufacturing practice	Item
Pull production	Production is “pulled” by the shipment of finished goods
	Production at stations is “pulled” by the current demand of the next station
	We use a “pull” production system
	We use Kanban, squares, or containers of signals for production control
Continuous flow	Products are classified into groups with similar processing requirements
	Products are classified into groups with similar routing requirements
	Equipment is grouped to produce a continuous flow of families of products
	Families of products determine our factory layout
Setup time reduction	Our employees practice setups to reduce the time required
	We are working to lower setup times in our plant
	We have low setup times for equipment in our plant
Statistical process control (SPC)	A large number of equipment/processes on shop floor are currently under SPC
	We extensively use statistical techniques to reduce process variance
	Charts showing defect rates are used as tools on the shop floor
	We use fishbone diagrams to identify the causes of quality problems
	We conduct process capability studies before product launches

Lean manufacturing practice	Item
Total productive maintenance (TPM)	We dedicate a portion of every day to planned equipment maintenance-related activities
	We maintain all our equipment regularly
	We maintain excellent records of all equipment maintenance-related activities
	We post equipment maintenance records on the shop floor for active sharing with employees
Employee involvement	Shop floor employees are key to problem-solving teams
	Shop floor employees drive suggestion programs
	Shop floor employees lead product/process improvement efforts
	Shop floor employees undergo cross-functional training

Part 3: Mapping of digitalization aspects

Please evaluate the digitalization of your company by answering the following questions on a scale from 1 to 5. To assist in the evaluation, examples of what 1 and 5 represent are supplied.

Aspect	Item	Example of "1"	Example of "5"
Shop floor digitalization	To what extent do you have a real-time view of your production and can dynamically react to changes in demand?	1: Not at all – Batch production for large lot sizes without insight into production status. No ability to react flexible on changes in demand	5: Virtual factory – Real-time view on production with capabilities to dynamically change schedules.
	How advanced is the digitalization of your production equipment (sensors, Internet of Things [IoT] connection, digital monitoring, control, optimization, and automation)?	1: Purely physical factory – Production equipment is entirely cut off from IT systems, and no real-time information can be gathered	5: Fully digitized factory – Interconnected production equipment allows for IT-access and information is fed into a virtual representation of the factory
	To what extent does your IT architecture (hardware) address the overall requirements of digitalization and Industry 4.0?	1: Not at all – The current architecture neither considers Industry 4.0 requirements (IoT, analysis of production data, etc.) directly nor is it easily adaptable for the new requirements)	5: Completely – All relevant requirements are explicitly considered in the IT architecture, the roadmap reflects enhancements to meet future needs
	To what extent do you use a manufacturing execution system (MES) or similar to control your manufacturing process?	1: Not at all – Production planning is done by hand without the support of a central IT system	5: Extensively – MES or similar is used for short-term planning (capacities, utilization, schedules, etc.), the system is highly integrated with ERP and shop floor system to enable vertical integration

Aspect	**Item**	**Example of "1"**	**Example of "5"**
Technologies for horizontal and vertical integration	How would you rate the degree of digitalization of your vertical value chain (from product development to production)?	1: No digitalization at all – No automated exchange of information along the vertical value chain (e.g., manual machine programming based on paper plans)	5: Complete digitalization – Continuous data flow along the vertical value chain (e.g., direct controlling of machines via CAD models, integration of ERP and MES)
	To what degree do you have an end-to-end IT-enabled planning and control process from sales forecasting, over production to warehouse planning and logistics?	1: Isolated planning processes – Neither IT-enabled nor integrated along the value chain (e.g., planning based on past experiences)	5: Integrated end-to-end planning system – Comprising real-time information along the entire value chain (e.g., sales forecasts directly affect production)
	How would you rate the degree of digitalization of your horizontal value chain (from customer order over supplier, production and logistics to service)?	1: No digitalization at all – No automated exchange of information along the horizontal value chain (e.g., no connection to supplier's IT systems)	5: Complete digitalization – Continuous data flow along the horizontal value chain (e.g., integration of logistic service providers into internal IT systems)
	How advanced is your IT integration with customers, suppliers and fulfillment partners?	1: No integration at all – Encapsulated IT systems allowing no access for external parties	5: Full integration – Interfaces for all relevant IT systems allowing seamless and secure data exchange (e.g., complete order tracking for customers, inventory insight for suppliers)
Organization and culture	How would you rate your capability to create value from data?	1: Limited – Large amounts of data are collected, but structured approaches for utilizing the data to enable business models are missing	5: Mature – Systematic approaches to leverage data for the optimization of operations and the fostering of new business models are in place (e.g., core analytics team, data scientists, etc.)
	How would you rate your capabilities and resources related to Industry 4.0 (e.g., data analytics, IoT, CPS, human-machine interface, production security, digital product lifecycle management, etc.) in your organization?	1: Limited – Lack of clarity on the presence or location of capabilities and absence of or confused responsibilities regarding Industry 4.0	5: Mature – Special units are anchored in the organization with overarching responsibilities for Industry 4.0 topics (e.g., a cross-functional "digital factory" unit)

Aspect	Item	Example of "1"	Example of "5"
Organization and culture	What level of involvement, support and expertise do executive and senior management have in your organization with regards to Industry 4.0?	1: Low leadership involvement – Senior management does not recognize the significance of Industry 4.0 and reveals almost no digital expertise	5: High leadership involvement – All senior management is fully knowledgeable and aware of the importance, workings and implication of Industry 4.0 (e.g., board of directors with a vision and roadmap)
	To which extent is your IT organization able to fulfill business requirements in the requested time, quality and cost?	1: Expectations regularly fall short – Implementation time and quality fail to meet business expectations (e.g., long lead times, inflexible IT processes, etc.)	5: Expectations are always met – The IT organization is able to react agile to new and changing requirements. Business and IT are perfectly aligned
	To which extent does your organization institutionalize collaboration on Industry 4.0 topics along with external partners such as academia, industry, suppliers or customers?	1: No collaboration – Industry 4.0 topics are if any, mostly investigated internally and outcomes are foreclosed towards external organizations	5: Open collaboration – Industry 4.0 innovation is fostered within open platforms designed for cross-industry research (e.g., "Smart Factory" environments, open laboratories for customers)

Part 4: Evaluation of operational performance

On a scale from 1 to 5, please indicate your current performance levels, as well as how they compare with your competitors and how your operational performance has evolved during the last five years.

Operational performance dimension	As compared with your competitors	Evolved during the last five years
Throughput time		
Product quality		
Process flexibility (changing between products)		
Process reliability (uptime)		
Production cost per unit		

Appendix B: Semi-Structured Interview Guide

A. Background

1. Please introduce yourself (position and responsibilities, career background, and years of employment).

B. Original lean solution and known challenges/limitations

2. Can you please describe the solution before it was digitalized?
3. What were the challenges and shortcomings of this solution? What was the motivation behind developing a digitalized solution?

C. Description of the digital lean manufacturing solution

4. How did you move from an analog to a digital solution?
    a. Which parts are digitalized?
    b. Did you develop your own solution or buy an existing solution?
    c. How long was the implementation process, and what were the main steps?
    d. Which data are collected, and how are they analyzed?

D. Benefits and limitations of the developed solution

5. What are the main changes observed after the digitalization?
6. What do you see as the main benefits of the digitalized solution?
7. What do you see as the main disadvantages and challenges of the digitalized solution?
8. In conclusion, do you think the digitalization of the existing solution improved it?

Part II: Collection of Papers

Paper 1

Buer, S.V., Strandhagen, J.O. & Chan, F.T.S. (2018), "The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924-2940.

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The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda

Sven-Vegard Buer[a], Jan Ola Strandhagen[a] and Felix T. S. Chan[b]

[a]Department of Mechanical and Industrial Engineering, NTNU, Norwegian University of Science and Technology, Trondheim, Norway; [b]Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Abstract: In recent years, Industry 4.0 has emerged as one of the most discussed concepts and has gained significant popularity in both academia and the industrial sector. Both Industry 4.0 and lean manufacturing utilise decentralised control and aim to increase productivity and flexibility. However, there have been few studies investigating the link between these two domains. This article explores this novel area and maps the current literature. This is achieved through a systematic literature review methodology, investigating literature published up to and including August 2017. This article identifies four main research streams concerning the link between Industry 4.0 and lean manufacturing, and a research agenda for future studies is proposed.

Keywords: Industry 4.0; smart manufacturing; lean manufacturing; cyber-physical systems; Internet of things; literature review

1 Introduction

Lean manufacturing is arguably the most prominent manufacturing paradigm of recent times (Womack, Jones, and Roos 1990; Holweg 2007). Lean manufacturing supports manufacturing companies in their efforts to improve in many areas, including reduced production cost, improved quality (Bhamu and Sangwan 2014), improved responsiveness by reducing lead times (Chauhan and Singh 2012), and increased flexibility (James-Moore and Gibbons 1997).

However, even if lean manufacturing has helped numerous companies reduce waste and thereby improve in several performance dimensions, many companies still struggle to successfully transform into a lean company (Jadhav, Mantha, and Rane 2014). Some companies fail to consider the strategic fit of lean practices, trying to implement it in environments where they are not applicable (Azadegan et al. 2013). Others might experience that the basic methods of lean manufacturing are not sufficient and hence do not meet the company's operational requirements (Kolberg and Zühlke 2015). Additionally, even if seemingly succeeding in their initial implementation phase, many companies find it difficult to sustain the initial momentum of their lean project (Netland 2016). To address these issues, it is relevant to investigate the solutions offered by information and communications technology (ICT).

Originating from the Toyota Production System, which can be traced back to the 1950s, lean manufacturing in its purest form is completely independent of any kind of ICT. However, the emergence of increasingly more advanced ICT solutions has increased the research effort into how lean manufacturing and ICT may cooperate to achieve better performance. Research into this area is summarised by, among others, Houy (2005), Ward and Zhou (2006), Riezebos, Klingenberg, and Hicks (2009), Powell (2013), and Maguire (2015). Evidence from industry also shows that companies are able to build hybrid solutions, where they are able to take advantage of both lean manufacturing and ICT solutions such as enterprise resource planning (ERP) systems (Riezebos, Klingenberg, and Hicks 2009) and manufacturing execution systems (MES) (Cottyn et al. 2011).

Despite numerous, recent studies investigating the interaction between ICT and lean manufacturing, few address the new possibilities introduced by Industry 4.0, also referred to as smart manufacturing (Kang et al. 2016). It has not been studied how an introduction of Industry 4.0 will influence already established management practices such as lean manufacturing and how already established lean practices will influence the implementation of Industry 4.0. Although having different approaches, Industry 4.0 and lean manufacturing share the same general objectives of increased productivity and flexibility (Frank 2014). The introduction of cyber-physical systems (CPS) and the Internet of things (IoT), key components of Industry 4.0, enable distributed computing and autonomy that is typically not found in traditional centralised ICT systems. This matches with traditional lean thinking, which favours decentralised structures with small modules and low levels of complexity (Thoben et al. 2014; Kaspar and Schneider 2015; Kolberg and Zühlke 2015) because complexity is enormously resource intensive (Kaspar and Schneider 2015).

The aim of the current article is to explore this novel area and present the current status of research regarding the link between Industry 4.0 and lean manufacturing. As a prerequisite for this, the key constructs are introduced and the postulated relationships between them are presented. Furthermore, the article identifies four research streams and presents key research findings in each area. Based on this, a research agenda for future studies is proposed.

The article is organised as follows: Section 2 introduces and defines the domain of Industry 4.0, while Section 3 outlines the connections between the main constructs and presents the conceptual framework that the current study is based on. Section 4 describes the research method, while the main findings from the literature review are presented in Section 5. In Section 6, the findings are discussed, and a research agenda is established, while Section 7 summarises and concludes the article.

2 The emergence of Industry 4.0

The pioneering proponents of the factory of the future found early on that inflexible and dedicated production lines should be exchanged with flexible machines and that computers will support this endeavour (Diebold 1952; Freeman 1988). The concept of ubiquitous computing was already envisioned more than 25 years ago by Mark Weiser (1991). Ubiquitous computing builds on the idea that computers are embedded throughout the environment, making them effectively invisible to the user (Weiser 1993). The rapid advances in ICT, exemplified by the introduction of technological solutions such as CPS and the IoT have ensured that this vision is coming closer to reality. The idea of an interconnected world has also gained attention from the industry sector, and the vision of a fourth industrial revolution is emerging, popularly known as Industry 4.0 (Kang et al. 2016). The increasingly affordable hardware and software solutions accelerate the transition towards the smart and interconnected factory envisioned by Industry 4.0 (Almada-Lobo 2016). With promises of manufacturing customised products at the same cost as mass production (Wang 2016), Industry 4.0 has gained significant popularity in both academia and in the industrial sector; companies worldwide are investing considerable sums into investigating how they can benefit from this emerging technology-based manufacturing paradigm.

Starting out as a German government programme to increase the competitiveness of their manufacturing industry (Kagermann et al. 2013), Industry 4.0 was announced at the Hannover Messe in 2011 (Drath and Horch 2014). It is a cooperation project between the private sector, academia and the government (Kang et al. 2016), and it revolves around '*networks of manufacturing resources (manufacturing machinery, robots, conveyor and warehousing systems and production facilities) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed and that also incorporate the relevant planning and management systems*' (Kagermann et al. 2013, 20). However, with time, the term Industry 4.0 has evolved into an overall label for describing the next era of manufacturing, and in this process, it has become a poorly defined buzzword for the future of production. Even though Industry 4.0 is one of the most frequently discussed topics among practitioners and academics in the last few years, no clear definition of the concept has been established; therefore, no generally accepted understanding of Industry 4.0 has yet been published (Brettel et al. 2014; Hermann, Pentek, and Otto 2016; Rüttimann and Stöckli 2016; Hofmann and Rüsch 2017). Researchers and practitioners have different opinions regarding which elements compose Industry 4.0, how these elements relate to each other and where Industry 4.0 is applicable. Surveys show that few practitioners are able to provide a concrete definition of Industry 4.0 (Heng 2014). Some even claim that Industry 4.0 does not bring something new, that it merely combines existing technologies and concepts into a new package with a catchy marketing name (Drath and Horch 2014). This ambiguity and lack of a clear definition will lead to communication difficulties and complicate research and education on the subject (Pettersen 2009), as well as make it more difficult for companies to identify and implement Industry 4.0 solutions (Hermann, Pentek, and Otto 2016).

Recent studies have found more than 100 different definitions of Industry 4.0 (Moeuf et al. 2017). Thus, it is important to clarify the definition used to ensure construct validity. In the current study, Industry 4.0 is operationalised as *the usage of intelligent products and processes, which enables autonomous data collection and analysis as well as interaction between products, processes, suppliers, and customers through the internet.* Similar to Liao et al. (2017), the relevant literature must be related to CPS, IoT, smart factories, or digitalisation.

3 Linking Industry 4.0 and lean manufacturing

The main point of interest for this article is to investigate the link between Industry 4.0 and lean manufacturing, as well as examine its implications on performance and the environmental factors influencing these relationships. Therefore, the first step is to develop a conceptual framework that explains the main constructs and the relationships between them.

Ohno (1988) describes the two pillars needed to support the Toyota Production System: just-in-time (JIT) and autonomation (jidoka). These pillars are also found in lean manufacturing (Bicheno and Holweg 2009). To successfully implement JIT, accurate and timely information sharing is a prerequisite (Haynes, Helms, and Boothe 1991; Zelbst et al. 2014). Accurate inventory data are especially important in lean supply chains because large buffers and safety stocks are eliminated. A digitalised supply chain will support this by providing timely and accurate data about inventory levels and location (Zelbst et al. 2014). Autonomation is about giving intelligence to the machines so that they autonomously can distinguish between normal and abnormal operations. Therefore, machines will stop if there is a problem, so no defective products are produced (Ohno 1988). The implementation of CPS in production gives machines intelligence and thereby facilitates autonomation. The machines will be able to report deviations faster, analyse the causes, and initiate measures automatically (Thoben et al. 2014).

Roy, Mittag, and Baumeister (2015) argue that the introduction of Industry 4.0 does not eliminate lean manufacturing but rather helps to increase the maturity of the firm's lean programme. Rüttimann and Stöckli (2016) predict that Industry 4.0 will materialise in pieces that have to be integrated into existing lean frameworks and will eventually increase the flexibility of lean manufacturing. The term *lean automation* slowly gained popularity throughout the 1990s, and it concerns developing automation solutions with a low level of complexity that fits lean production environments (Jackson et al. 2011). The new possibilities enabled by Industry 4.0 have reignited some of the research within this field (Kolberg and Zühlke 2015; Kolberg, Knobloch, and Zühlke 2017).

Lean manufacturing focuses on eliminating all kinds of waste in the production process by identifying any unnecessary activities, streamlining the process, and creating standardised routines. Simple machines and workstations with low levels of complexity facilitate automation and digitalisation of the manufacturing process (Kolberg and Zühlke 2015). Lean manufacturing also emphasises visual control and transparency, which makes it easier to identify problems in the process. This has led to some researchers claiming that a lean implementation necessarily must be seen as a prerequisite for a successful Industry 4.0 transformation (Kaspar and Schneider 2015; Staufen AG 2016). Based on a survey of 179 industrial companies, Staufen AG (2016) find that the similarity between the Industry 4.0 pioneers is that they have already implemented a lean manufacturing system, which may show lean is an ideal foundation when shifting towards Industry 4.0. Khanchanapong et al. (2014) similarly suggest that advanced manufacturing technologies (AMTs) may need to be supported by lean practices to maximise the manufacturing performance increase.

The performance benefits of implementing lean manufacturing are proven in numerous cases and concern a broad range of different performance metrics. Marodin and Saurin (2013) classify the performance benefits of implementing lean manufacturing into five groups: (1) operational, (2) financial, (3) human, (4) market, and (5) environmental. Duque and Cadavid (2007) further define how specific lean practices are affecting different operational performance metrics. From cases reported in the literature, Moeuf et al. (2017) investigate the observed performance benefits of implementing Industry 4.0; they find that increased flexibility is the most common reported performance benefit, followed by improved productivity, reduced cost, reduced delivery time, and improved quality. Regarding the performance impacts of combining lean manufacturing with AMTs, Khanchanapong et al. (2014) find that the synergistic performance impact of such an integration motivates the joint optimisation of the two rather than optimising either resource alone.

The contingency theory states that organisations have to adapt their structures to fit with their environment to achieve high performance (Donaldson 2001; Sousa and Voss 2008). To distinguish among different environments, internal and external environmental factors that can influence the organisation should be mapped. Thus, an environmental factor is defined as *an identifiable element in the environment that influences the organisation's operations.*

In addition to the moderating effect on performance, environmental factors tend to influence the applicability and implementation approach of improvement programmes (Netland 2016). Lean manufacturing emerged from the automotive industry and has successfully been adopted by other repetitive production environments. However, the extent to which lean principles are suitable for non-repetitive environments has been questioned (Cooney 2002). The lean practices and methods developed for mass production do not usually fit these environments (Horbal, Kagan, and Koch 2008; Matt 2014), which tend to experience major difficulties when seeking to implement lean practices (Portioli-Staudacher and Tantardini 2012). Similarly, for Industry 4.0, it is argued that environmental factors will have a significant impact on the applicability of Industry 4.0. Through a multiple case study, Strandhagen et al. (2017) find that companies with repetitive production systems on a general basis should have an easier transition to Industry 4.0 than non-repetitive production systems. Other researchers claim that only big enterprises will be able to reap the benefits from Industry 4.0 and that small and medium-sized enterprises (SMEs) can quickly become the victims of Industry 4.0 (Sommer 2015). Smaller enterprises will suffer because of the high investments needed, and the increased flexibility introduced by Industry 4.0 will allow bigger enterprises to steal market shares for customised products, a market segment now usually dominated by SMEs (Rüttimann and Stöckli 2016).

From the literature presented above, Figure 1 illustrates the different theoretical lenses regarding the relationships between Industry 4.0, lean manufacturing, performance, and environmental factors. The purpose of the conceptual framework in Figure 1 is to establish a structure for summarising the literature findings presented in Section 5. The four relationships in the framework are described as follows:

a) Industry 4.0 technologies can support and further develop well-known lean manufacturing practices, that is, *Industry 4.0 supports lean manufacturing.*

b) Established lean manufacturing systems exert facilitating effects on Industry 4.0 implementations, that is, *lean manufacturing supports Industry 4.0.*

c) The changes imposed on the production system by the integration of Industry 4.0 and lean manufacturing affects different performance dimensions of the system, that is, it illustrates the *performance implications of an Industry 4.0 and lean manufacturing integration.*

d) Based on similar studies, it is likely that environmental factors influence the potential to integrate Industry 4.0 and lean manufacturing, as well as the resulting performance of such an integration, that is, it depicts *the effect of environmental factors on an Industry 4.0 and lean manufacturing integration.*

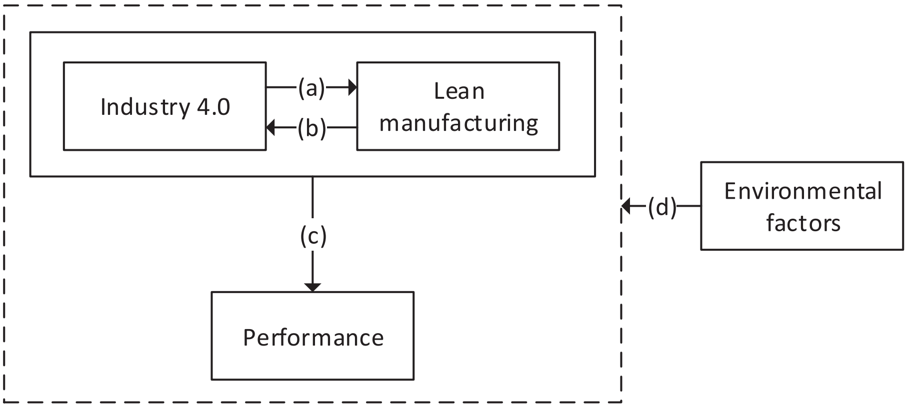

Figure 1: Conceptual framework illustrating the relationships between Industry 4.0, lean manufacturing, performance and environmental factors

4 Research method

This literature review is based on a systematic literature review approach, which ensures replicability by using transparent steps. A systematic review establishes a firm foundation for future research and facilitates theory development, aligns existing research, and uncovers areas where additional research is needed (Webster and Watson 2002).

Based on the extensive literature review by Liao et al. (2017), search terms connected to Industry 4.0 were selected. Liao et al. (2017) present a list of phrases that are the most related to and commonly used together with Industry 4.0. Based on these keywords and the operational definition presented in Section 2, a comprehensive list of Industry 4.0 search terms was established (Appendix 1). Lean manufacturing is a considerably more established domain than Industry 4.0, and we therefore assumed that it is sufficient to use the two search terms ‘lean manufacturing’ and ‘lean production’.

The literature searches were conducted through the academic databases Scopus, ProQuest, Web of Science, ScienceDirect, and EBSCO. Table 1 presents the number of search results in each database. Scopus by far returned the most results, while ScienceDirect and EBSCO returned the fewest.

Table 1: Search results in each of the databases

	Scopus	**ProQuest**	**Web of Science**	**ScienceDirect**	**EBSCO**
Results	57	18	17	8	7

An important part of any systematic literature review is to establish inclusion and exclusion criteria (Meline 2006). This ensures an objective reasoning behind the choice of literature. The inclusion criteria, guiding the choice of databases and filtering settings in the database, are as follows: only peer-reviewed academic *journal articles, conference articles,* or *book sections* available up to and including August 2017 were considered. After obtaining the initial set of articles from the different databases, the first step was to remove duplicates. Table 2 illustrates the duplication between the five databases used. EBSCO and Scopus had the highest duplication percentage, where 85.7% of the articles found in EBSCO also could be found in Scopus. On the other hand, ScienceDirect had no duplicate results with neither ProQuest nor EBSCO.

Table 2: Duplication of search results among the databases

	Scopus	**ProQuest**	**Web of Science**	**ScienceDirect**	**EBSCO**
Scopus	-	-	-	-	-
ProQuest	5	-	-	-	-
Web of Science	12	4	-	-	-
ScienceDirect	5	0	4	-	-
EBSCO	6	4	5	0	-

Next, the first screening process investigated the titles and abstracts of the identified articles and excluded articles that were: (1) not in English, (2) not a peer-reviewed academic article, (3) not related to Industry 4.0 and lean manufacturing, or (4) without a full text published online. For the remaining articles, full-text articles were collected and screened. Articles were excluded in this second screening process if they were considered only vaguely related to this topic. The typical examples of articles excluded because of this criterion are articles that mention Industry 4.0 and/or lean manufacturing as examples without further analysis between the two. The inclusion and exclusion criteria are summarised in Table 3. The remaining articles at this stage were included in the literature analysis.

Table 3: Inclusion and exclusion criteria

Inclusion criteria	Document type: *Journal article, conference article* or *book section*
Exclusion criteria	Non-English (NE) Not peer-reviewed academic literature (NP) Not related to Industry 4.0 and lean manufacturing (NR) No full text (NF) Vaguely related to Industry 4.0 and lean manufacturing (VR)

Based on this methodology, the initial sample of 107 articles was reduced to 21 articles for the literature analysis. As shown in Figure 2, the process of filtering articles is depicted according to the PRISMA flowchart. Out of the 21 articles included in the analysis, 18 of these could be found in the Scopus database. This indicates that Scopus is the most relevant academic database for finding articles relating to the integration of Industry 4.0 and lean manufacturing.

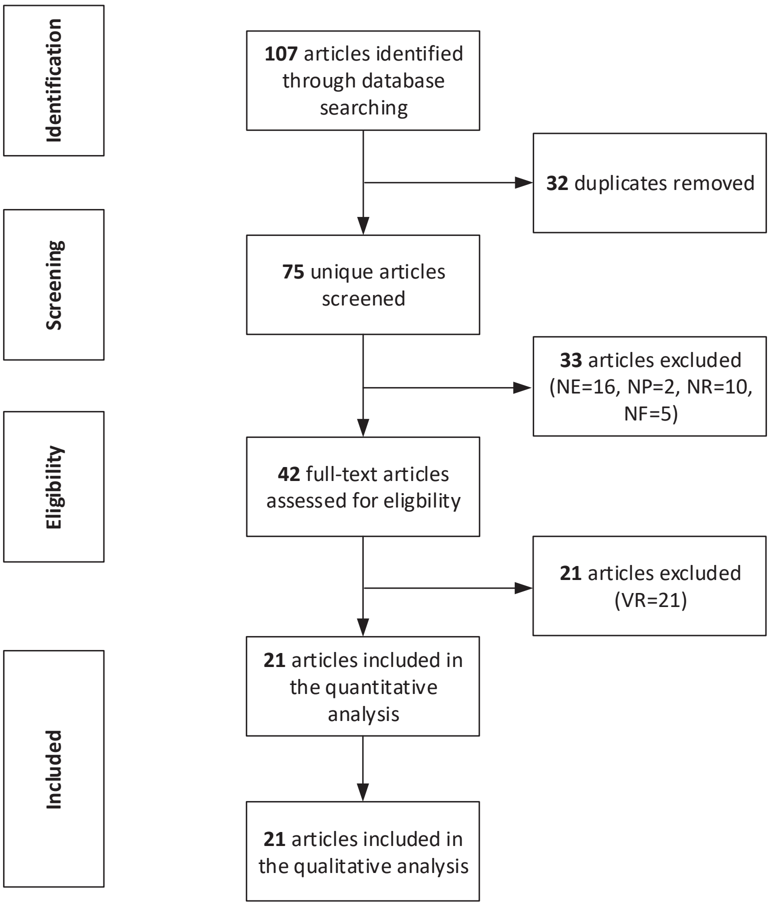

Figure 2: The PRISMA flowchart illustrates the different phases in the systematic literature review (Adapted from Moher et al., 2009). See Table 3 for explanations of the exclusion codes.

The relevant articles were collected in a database where they were sorted, categorised and had their main theoretical standpoint and findings extracted. The software used for this was EndNote X7 for reference management and NVivo 11 for coding the literature.

5 Presentation of the current literature on the link between Industry 4.0 and lean manufacturing

The review identified 21 articles that comply with the inclusion and exclusion criteria and thus present a contribution towards explaining the link between Industry 4.0 and lean manufacturing. This section will first give an overview of the articles included in the analysis before classifying them according to the conceptual framework presented in Section 3. The most important findings are then presented according to the proposed classification scheme.

5.1 An overview of the included literature

Table 4 presents both the number of articles published per year as well as the research methods utilised. It is clear that this is an emerging research area, with most of the studies being published in 2016 and 2017. Out of the 21 articles in the final sample, 11 of the articles are conference articles while 10 are journal articles. Germany is the biggest contributor, with six of the articles originating from German universities or research institutions.

Table 4: Research methods in the investigated articles

	Action research	Case study	Experimental	Mixed methods	Conceptual	Literature review	Total
2014	1	-	1	-	-	-	2
2015	-	-	-	1	1	-	2
2016	2	1	-	2	3	1	9
(2017)	1	1	1	2	2	1	8
Total	4	2	2	5	6	2	-

5.2 Key findings and literature classifications

By using the proposed conceptual framework to categorise the articles, it is easy to identify the main theoretical perspective of the article and the areas it investigates. Because the current study investigates the links between established constructs rather than the constructs themselves, the articles are categorised according to the four arrows describing the relationships, where each arrow represents a subsection in the review. Figure 3 presents the classification of the articles.

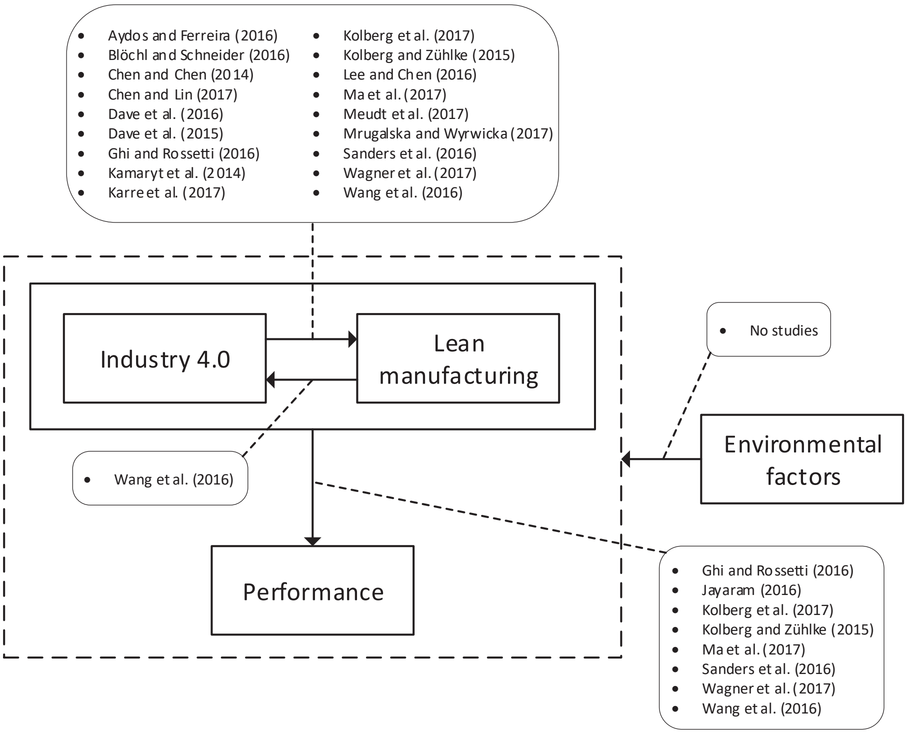

Figure 3: Categorisation of the articles according to the proposed conceptual framework

5.2.1 *Industry 4.0 supports lean manufacturing*

This section reviews the existing literature that discusses how Industry 4.0 can support lean manufacturing, both in the implementation phase and for established lean systems.

Sanders, Elangeswaran, and Wulfsberg (2016) investigate the different dimensions of lean manufacturing and how Industry 4.0 solutions might help overcome lean implementation barriers. They list 23 different lean implementation barriers and propose viable solutions from the Industry 4.0 domain. Value stream mapping (VSM) is a fundamental lean tool and often seen as a starting point in a lean implementation process. It is used to map the current process and identify improvement areas in the value stream. Traditional VSM is a manual 'pen-and-paper' process, and the data collection for it can often be challenging and tedious. In addition, it only offers a 'snapshot' of the process, and small changes could change this picture dramatically. Industry 4.0 can enhance VSM through the real-time collection of data (Chen and Chen 2014; Meudt, Metternich, and Abele 2017; Mrugalska and Wyrwicka 2017). Meudt, Metternich, and Abele (2017) introduce the concept of 'Value stream mapping 4.0'. Their method mainly focuses on information logistics and is a tool for detecting wastes in the information flows within a company. Chen and Chen (2014) propose a real-time VSM system that can assist companies in their lean implementation by automatically creating value stream maps. By automating data collection, both the time spent on collecting data and the probability of error are reduced. In addition, a dynamic picture of the shop floor is created, which increases the information visibility and supplies the decision makers with accurate and real-time information (Chen and Chen 2014). This kind of real-time VSM offers excellent possibilities for waste reduction, as well as immediate feedback on decisions. This facilitates experiments in production, for instance, related to batch sizes and production sequencing.

Companies that have already implemented lean manufacturing need guidelines on how to react to the impacts of Industry 4.0 (Meudt, Metternich, and Abele 2017). These companies need to integrate the new technologies from Industry 4.0 into their existing lean manufacturing systems (Wagner, Herrmann, and Thiede 2017), but the knowledge of how this should be done is still immature (Kolberg and Zühlke 2015; Wagner, Herrmann, and Thiede 2017). It is unclear which practices could be combined, which ones complement each other and which contradict each other. Among others, this knowledge will be important in the endeavour to tailor company-specific production systems.

Blöchl and Schneider (2016) claim that processes designed according to lean principles can be further optimised to deal with higher complexity by using Industry 4.0 technology. Similarly, Wang et al. (2016) claim that smart manufacturing can help companies achieve a higher level of lean, and investigate the impact on lean manufacturing from technologies related to data collection, big data analysis, and integrated processes. Wagner, Herrmann, and Thiede (2017) investigate what impact Industry 4.0 will have on existing lean practices. Together with Industry 4.0 and lean manufacturing practitioners, they develop an impact matrix that can be used as a decision support tool on how to integrate these emerging technologies into existing lean systems. Karre et al. (2017) describe the planned transition of a lean learning factory towards an Industry 4.0 state. In the article, they present numerous ideas on how lean practices can be enhanced using Industry 4.0 technologies. Ma, Wang, and Zhao (2017) claim that the emergence of Industry 4.0 has widened the application range of Jidoka and presents a smart Jidoka system based on CPS technologies. Chen and Lin (2017) argue how 3D printing can facilitate some objectives of lean manufacturing, such as one piece flow and JIT deliveries.

The analysed articles present several scenarios on how Industry 4.0 can enhance traditional lean manufacturing practices. Table 5 summarises these findings by illustrating which studies discuss the impact of Industry 4.0 on which lean practices. The lean practices presented have been cross-referenced with the review by Pettersen (2009) to ensure that they are inside the lean manufacturing domain. Table 5 further differentiates between ‘hard’ and ‘soft’ lean practices. ‘Hard’ refers to the technical and analytical practices used in lean, while ‘soft’ concern people and relations (Bortolotti, Boscari, and Danese 2015). This categorisation will be discussed further in Section 6.

Table 5: Studies investigating Industry 4.0 impacts on specific lean practices

	Lean practice	Chen and Chen (2014)	Chen and Lin (2017)	Karre et al. (2017)	Kolberg, Knobloch, and Zühlke (2017)	Kolberg and Zühlke (2015)	Ma, Wang, and Zhao (2017)	Meudt, Metternich, and Abele (2017)	Mrugalska and Wyrwicka (2017)	Sanders, Elangeswaran, and Wulfsberg (2016)	Wagner, Herrmann, and Thiede (2017)	Wang et al. (2016)
'Hard' lean practices	Andon				**X**	**X**	**X**		**X**	**X**	**X**	
	Heijunka				**X**						**X**	
	Just-in-time deliveries				**X**	**X**						
	Kanban		**X**		**X**	**X**		**X**	**X**	**X**	**X**	**X**
	Man-machine separation										**X**	
	One piece flow		**X**	**X**							**X**	**X**
	Poka Yoke					**X**			**X**			
	Single-minute exchange of die			**X**		**X**			**X**	**X**		
	Standardized work										**X**	
	Statistical process control			**X**	**X**	**X**				**X**		
	Takted production										**X**	
	Total productive maintenance			**X**								
	Value stream mapping	**X**						**X**	**X**			
	Waste reduction										**X**	
'Soft' lean practices	5S		**X**								**X**	
	Kaizen								**X**		**X**	
	People and teamwork										**X**	

5.2.2 *Lean manufacturing supports Industry 4.0*

Another perspective on the interaction between Industry 4.0 and lean manufacturing is that lean manufacturing can be used as a foundation to build an Industry 4.0 implementation on. The streamlined and waste-free process obtained through a lean transformation simplifies further efforts to automate and digitalise the manufacturing process.

Wang et al. (2016) argue that a production process that already has implemented lean manufacturing is more likely to be modelled and controlled. Therefore, they argue that this environment is an easier foundation for building a smart manufacturing platform on.

5.2.3 *Performance implications of an Industry 4.0 and lean manufacturing integration*

A key area of interest for most improvement programmes is their effect on performance. Some authors conceptualise the possible performance benefits of an Industry 4.0 and lean manufacturing integration. Others have empirical evidence based on experimental demonstrators, case studies, or action research in actual production environments.

Sanders, Elangeswaran, and Wulfsberg (2016) argue how Industry 4.0 together with lean manufacturing can improve productivity, reduce waste and consequently reduce costs. Kolberg and Zühlke (2015) describe how modular workstations and flexible manufacturing lines working together with single-minute exchange of die can reduce the set-up time. They also argue for how autonomous Kanban bins that can detect their inventory level and automatically order parts from suppliers can help reduce inventory levels. Ma, Wang, and Zhao (2017) show how CPS-based smart Jidoka is a cost-efficient and effective approach to improve production system flexibility. They also prove other benefits such as increased reliability and reduced cost. Table 6 illustrates the identified performance benefits reported in the investigated articles. However, the studies have only focused on operational performance metrics.

Table 6: Studies evaluating the performance benefits of integrating Industry 4.0 and lean manufacturing

	Conceptual research			**Empirical research**				
Performance dimension	Ghi and Rossetti (2016)	Jayaram (2016)	Sanders, Elangeswaran, and Wulfsberg (2016)	Kolberg, Knobloch, and Zühlke (2017)	Kolberg and Zühlke (2015)	Ma, Wang, and Zhao (2017)	Wagner, Herrmann, and Thiede (2017)	Wang et al. (2016)
Cost			**X**			**X**		
Flexibility			**X**	**X**	**X**	**X**		**X**
Productivity			**X**					**X**
Quality	**X**	**X**						
Reduced inventory				**X**	**X**		**X**	
Reliability						**X**	**X**	

5.2.4 *The effect of environmental factors on an Industry 4.0 and lean manufacturing integration*

The literature review uncovered no articles studying the effect of environmental factors on an Industry 4.0 and lean manufacturing integration *per se*. However, some knowledge can be gathered by investigating in which sectors the studies were conducted. Although this will not give any information regarding in which sectors an Industry 4.0 and lean manufacturing integration is *not* beneficial, it will give some hints regarding which sectors research has already been carried out in. Table 7 presents an overview of the relevant studies, showing that with the exception of the study from the construction industry, most studies are from typical repetitive production environments.

Table 7: Overview of the studies on integrating Industry 4.0 and lean manufacturing in different sectors

Sector	Aydos and Ferreira (2016)	Chen and Chen (2014)	Dave et al. (2016)	Ma, Wang, and Zhao (2017)	Wagner, Herrmann, and Thiede (2017)
Automotive				**X**	**X**
Construction			**X**		
Forging	**X**				
Machining	**X**				
Parts manufacturing		**X**			

6 Pointing out future research directions

The current article has reviewed the existing literature regarding the link between Industry 4.0 and lean manufacturing. It is clear that this is a growing research area, reflecting the current trend in the industrial sector. This section discusses the findings from the literature review and points out a research agenda based on the identified gaps in the literature.

The literature review only identified 21 relevant academic articles, which is surprising because of the popularity of these two domains in recent years. Given the sizeable proportion of companies that currently have implemented some form of lean manufacturing, this calls for more research to ensure that companies can base their future improvement projects on a solid theoretical foundation.

The proposed agenda for future research is based on what the current body of literature insufficiently addresses or answers. Future research should focus on filling in these evident gaps in the literature. Research gaps in the following five areas have been pointed out:

1. The impact of Industry 4.0 on ‘soft’ lean practices
2. The facilitating effects of lean manufacturing on Industry 4.0 implementations
3. Empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration
4. The effect of environmental factors on the integration of Industry 4.0 and lean manufacturing
5. Implementation framework for moving towards an Industry 4.0 and lean manufacturing integration

6.1 The impact of Industry 4.0 on 'soft' lean practices

As seen in Table 5, most of the studies investigate how Industry 4.0 can enhance the 'hard' practices of lean. There have been few studies investigating how the introduction of Industry 4.0 will impact the shop floor initiatives typically associated with lean, such as continuous improvement efforts (Kaizen), teamwork, workforce involvement and autonomy, and 5S. Although sometimes overlooked, these so-called soft practices are crucial not only for achieving high performance through lean manufacturing, but also for sustaining performance in the long term (Bortolotti, Boscari, and Danese 2015).

It is known that improvement projects tend to fail if workers start feeling that their jobs are threatened (Womack 1996). It is therefore important for companies to ensure employees that no one will be laid off, but that the company rather will be seeking new market opportunities. If not, the organisation might end up with a situation that resembles a *continuous improvement paradox*, in which employees, through optimising the process, make themselves redundant. The increased automation levels also change the shop floor landscape, leading to a decrease in standardised low-skill work and an increase in high-skill activities. This means that continuous learning, training, and education of the workforce will be essential to adapt to the qualification requirements resulting from Industry 4.0 (Bonekamp and Sure 2015).

There is evidence that involving employees in Kaizen events positively affects their job satisfaction (Smith 2003). Other stated benefits of continuous improvement efforts include increased employee commitment, improved performance, quality, and customer satisfaction, together with reduced waste and costs (Fryer, Antony, and Douglas 2007). The increased process complexity will indeed influence the possibilities for shop floor personnel to involve themselves in improvement projects. A central question is consequently how the increase in process complexity following an Industry 4.0 transformation will affect the usage of 'soft' lean practices and, in turn, how this impacts both the job satisfaction and operational performance.

6.2 The facilitating effects of lean manufacturing on Industry 4.0 implementations

> *'The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency. The second is that automation applied to an inefficient operation will magnify the inefficiency'.* – Bill Gates (cited in Krishnan (2013))

This quote illustrates why lean thinking is still important in an increasingly automated and digitalised world. It highlights the inevitable fact that an inefficient process that is automated is still inefficient (Nicoletti 2013) and is basically automating some type of waste. The cost of automating an inefficient process also tends to be higher (Kaspar and Schneider 2015).

Although the literature gives some indications on the facilitating effects of implementing lean prior to an Industry 4.0 transformation, no study has investigated this topic in-depth. The existing studies typically handle this question at a high level, without investigating whether there are specific parts of lean that are causing this effect. An interesting aspect would be to investigate whether the 'hard' aspects of lean, such as the organisation of production resources, are the most important ones for this effect or whether it is the 'soft' aspects of lean. Future studies should investigate the reasons behind this phenomenon and how it affects implementation frameworks for Industry 4.0.

6.3 Empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration

Table 6 presents the current studies discussing the performance impacts of combining Industry 4.0 and lean manufacturing. However, several of these studies only discuss and hypothesise on a conceptual level, while some of the empirical studies collect their data from secondary sources. To motivate an Industry 4.0 and lean manufacturing integration, it is necessary to further investigate the potential performance implications through empirical studies. Although the current sample of studies gives some indications on the potential performance impacts, the studies are clearly insufficient in both width and depth. Central research issues in the future will be to measure what a successful Industry 4.0 and lean manufacturing integration entails, as well as comparing the performance impacts with those of a 'pure' Industry 4.0 or lean manufacturing system.

6.4 The effect of environmental factors on the integration of Industry 4.0 and lean manufacturing

As discussed in Section 3, it is likely that environmental factors will affect both the potential to integrate Industry 4.0 and lean manufacturing, as well as the resulting performance of the integration. The literature review found no studies that neither confirmed nor denied this hypothesis, still leaving this as a research gap. The sector analysis in Table 7 shows that most of the current studies have been conducted in repetitive production environments, which is similar to where both Industry 4.0 and lean manufacturing separately have been deemed most applicable by earlier studies.

Future research should focus on how environmental factors both affect the performance and compatibility of the two domains. These are critical issues to investigate in the endeavour to identify which environments might reap the largest benefits of an Industry 4.0 and lean manufacturing integration. An example of a promising research area is whether Industry 4.0 can assist in making lean manufacturing applicable in environments where it previously has been deemed unsuitable.

6.5 Implementation framework for moving towards an Industry 4.0 and lean manufacturing integration

The immaturity of this research area is a natural explanation for why no implementation framework for an Industry 4.0 and lean manufacturing integration has been published in the literature. It is important to gain a more in-depth understanding of how these two domains interact before an implementation framework can be proposed, and the four prior research gaps are all important in this respect.

Numerous implementation frameworks for lean manufacturing have been proposed (Bhamu and Sangwan 2014), and guidelines for implementation of Industry 4.0 are starting to emerge (Hermann, Pentek, and Otto 2016). These existing frameworks can be used as a starting point, similar to the work of Powell et al. (2013), who use existing implementation frameworks for ERP and lean manufacturing as a basis to propose a framework for a concurrent implementation process of the two.

Future research should investigate whether there is a preferred implementation sequence of the two domains. Should Industry 4.0 and lean manufacturing be implemented concurrently or sequentially? If they should be implemented sequentially, which one should be implemented first? Further, how will the performance be affected by a concurrent or sequential implementation? How do environmental factors influence these issues?

6.6 What can we learn from earlier studies?

An interesting research approach that should be explored further is how the findings from studies on earlier technological shifts can be used to support research on Industry 4.0. One example of this approach is the review by Maghazei and Netland (2017), who examine how existing literature on AMTs can support the current stream of Industry 4.0 research.

In addition to the existing stream of research on lean automation, another example of an interesting field to explore is the research related to radio frequency identification (RFID) technologies and lean manufacturing. Parts fitted with a RFID chip can, by using tracking equipment, be traced throughout the supply chain (Powell and Skjelstad 2012), and the usage of RFID thus has conceptual similarities with Industry 4.0. Patti and Narsing (2008) investigate the compatibility of lean manufacturing and RFID by asking whether they are competitive or compatible; they argue that RFID can coexist with and support lean implementations. Rafique et al. (2016) investigate how an introduction of RFID technology affects lean implementation barriers. They argue that the capabilities of RFID, such as *real-time traceability* and *automated information visibility,* might help overcome several of the stated lean implementation barriers.

Researchers are therefore encouraged to, in addition to the other areas outlined above, investigate the existing knowledge in adjacent areas to discover how existing findings, propositions, and theories can be transferred to an Industry 4.0 setting. Sometimes, the answers to the future lie in the past.

7 Conclusion

Despite the rapidly increasing popularity of Industry 4.0, no study has so far gathered and presented the scattered literature on how Industry 4.0 relates to the popular field of lean manufacturing. The current article has proposed a conceptual framework that can be used to classify the studies published so far and has given an overview of the current findings and research gaps. The literature findings are classified into four research streams: *(1) Industry 4.0 supports lean manufacturing, (2) lean manufacturing supports Industry 4.0, (3) performance implications of an Industry 4.0 and lean manufacturing integration,* and *(4) the effect of environmental factors on an Industry 4.0 and lean manufacturing integration.* It is clear from the findings that this area is still immature, with seemingly no common platform of knowledge to build the research on. The current article proposes further research in the following five areas: *(1) the impact of Industry 4.0 on 'soft' lean practices, (2) the facilitating effect of lean manufacturing on Industry 4.0 implementations, (3) empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration, (4) the effect of environmental factors on the integration of Industry 4.0 and lean manufacturing,* and *(5) implementation framework for moving toward an Industry 4.0 and lean manufacturing integration.* The current article should be seen as the first step to converge this new field of research by establishing a framework that can be used as a foundation for future studies and giving a research agenda, which by pointing out the most apparent research gaps, can inspire and guide future research efforts.

7.1 Contribution to theory

As the first systematic literature review in this area, the current article provides a thorough presentation of the current literature and theoretical standpoints regarding the link between Industry 4.0 and lean manufacturing. The conceptual framework presented in Section 3 describes the relationships between the main constructs investigated in this study and is supported by the literature findings. The current body of research has mainly focused on how Industry 4.0 technologies can be used to support existing lean practices, with most of the emphasis on Andon and Kanban. Most of the studies investigating the performance implications of such an integration claim that increased flexibility will be the main benefit, similar to what the proponents of Industry 4.0 claim it will entail. Although there are no studies explicitly discussing the applicability of an integrated Industry 4.0 and lean manufacturing system in different environments, most use cases are reported from repetitive production environments.

The proposed research agenda guides future research efforts based on what the current research insufficiently addresses or answers. It encourages researchers not only to focus on how Industry 4.0 can enhance the technical solutions of lean manufacturing, but also how it impacts the 'soft' aspects of lean. The effects of established lean manufacturing systems on the ease of implementing Industry 4.0 are another important research area, one relevant for a large number of companies aiming to transform their operations using the emerging ICT solutions. There is also a call for additional empirical research regarding the actual performance benefits of such an integrated solution, together with a future need for synthesising the knowledge into an implementation framework.

7.2 Contribution to practice

A literature review offers a quick introduction to the current body of knowledge and is thus a helpful tool for practitioners seeking the most recent research findings. Table 5 can be used as a starting point for practitioners wishing to investigate how the emerging ICT solutions associated with Industry 4.0 can be used to enhance lean practices. Table 6 gives an indication of which performance metrics are affected through an Industry 4.0 and lean manufacturing integration and will thus work as a reference point for practitioners seeking to improve specific performance areas. Similarly, Table 7 gives an overview of the sectors where the implementations of integrated solutions have been reported in the literature.

7.3 Limitations

The limitations of the current study must also be highlighted. Although using a systematic literature review approach using five different scholarly databases, some studies might have been overlooked because of the researchers' choice of search terms and databases. There were also some articles excluded because they were not in English, ones that might have contained relevant findings. Lastly, the small number of articles dealing with an Industry 4.0 and lean manufacturing integration is not ideal when aiming towards drawing general conclusions.

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Appendix 1

Table A1: Search key words (“Part 1” AND “Part 2”)

Part 1	Part 2
"Industry 4.0"	"lean manufacturing"
OR	OR
"Industrie 4.0"	"lean production"
OR	
"the fourth industrial revolution"	
OR	
"the 4th industrial revolution"	
OR	
"smart manufacturing"	
OR	
"smart production"	
OR	
"smart factory"	
OR	
"smart factories"	
OR	
"cyber physical system"	
OR	
"cyber physical production system"	
OR	
"internet of things"	
OR	
"industrial internet"	
OR	
"big data"	
OR	
"digitalization"	
OR	
"digitization"	
OR	
"digitalisation"	
OR	
"digitisation"	

Paper 2

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Strategic Fit of Planning Environments: Towards an Integrated Framework

Sven-Vegard Buer (✉), Jo Wessel Strandhagen, Jan Ola Strandhagen,
and Erlend Alfnes

Department of Mechanical and Industrial Engineering,
NTNU, Norwegian University of Science and Technology, Trondheim, Norway

`{sven.v.buer,jo.w.strandhagen,ola.strandhagen,erlend.alfnes}`
`@ntnu.no`

Abstract: Numerous studies have highlighted the importance of achieving a strategic fit between the actual planning environment and the production planning and control systems that are employed. Failing to achieve this strategic fit often leads to suboptimal solutions which in turn negatively affects production planning and control performance. Through using a literature study methodology, a comprehensive planning environment mapping framework is developed and tested through investigating five manufacturing companies. The framework also investigates the causality between planning environment variables. The results from the mapping can be used as a starting point for designing appropriate production planning and control solutions, comparing companies, and identifying possible improvement areas.

Keywords: Planning environments, Strategic fit, Production planning and control

1 Introduction

Fierce competition in today's business environment puts companies under a tremendous pressure to innovate their operations strategies and practices in order to meet the changing requirements of the market [1]. These days, companies have to compete based on numerous performance objectives such as *price, quality*, and *responsiveness* [1, 2], as well as *flexibility* and *dependability* [3]. Because of this requirement to excel in a variety of dimensions and the steadily increasingly complexness of the environments in which companies operate, the need to assure a strategic fit between the production planning and control (PPC) system and the planning environment is more important than ever [4]. The lack of fit between characteristics of the planning environment and the PPC system will negatively influence the performance of the manufacturing firm [5, 6].

In order to achieve fit, it is important that the company identifies the key characteristics, both internal and external, which influences their planning environment. Jonsson and Mattsson [6] argue that knowing the actual planning environment is fundamental in order to use the appropriate planning methods for the specific environment. This is supported by Schönsleben [7], who also mentions that planning environment variables may be used for comparing results within the company or the supply chain to reveal issues that hinder an efficient supply chain. He also states that in order to compare performance indicators among different companies effectively, these variables should be taken into account.

Motivated by the importance of achieving strategic fit, this paper aims at developing a comprehensive framework for mapping a company's planning environment. This mapping can be used as a starting point for selecting appropriate PPC methods, comparing companies, and identifying possible improvement areas.

Through utilizing a literature study methodology, different existing frameworks for mapping planning environments have been identified and analyzed. Through analyzing their similarities and differences, it has been possible to assess the variables that are critical in a mapping process. These have been used as a basis to develop the integrated framework. In addition, to test the developed framework, case samples from five manufacturing companies have been collected.

This paper is an extended version of 'Frameworks for Strategic Fit of Planning Environments: A Case Based Exploratory Study' presented at the 6th International Conference on Information Systems, Logistics and Supply Chain (ILS 2016) (see [8]). The paper is structured as follows: Chapter 2 outlines the importance of PPC for manufacturing companies, while Chapter 3 investigates existing frameworks for mapping companies' planning environments. The development process of the framework and its variables are presented in Chapter 4. The results from testing the developed framework on a set of case companies are presented in Chapter 5, while Chapter 6 discusses the causality of variables and the possible usage areas of the framework. The paper is concluded and future work is outlined in Chapter 7.

2 The Importance of Production Planning and Control

PPC can be described as the activities required to match supply and demand [9], and is concerned with scheduling, coordinating, and organizing operations activities [10]. Vollmann, Berry, Whybark and Jacobs [9] define PPC as the tasks required to: '… manage efficiently the flow of material, the utilization of people and equipment, and to respond to customer requirements by utilizing the capacity of our suppliers, that of our internal facilities, and (in some cases) that of our customers to meet customer demand'. The importance of PPC for a manufacturing company to stay competitive and profitable is undeniable [9, 11], and poor PPC performance has often been found as a major reason for company bankruptcy [9]. An effective PPC system can contribute to competitive performance by lowering costs and providing greater responsiveness to the market [9]. Further, Vollmann, Berry, Whybark and Jacobs [9] highlight that both the production process in a company and their market requirements have implications for the PPC design, as illustrated by Bertrand, Wortmann and Wijngaard [12] in their case studies of four diverse companies.

The customer order decoupling point (CODP) is the point in the manufacturing value chain for a product where the product is linked to the specific customer order. Thus, it is the point that separates production based on forecasts and plans, from production based on an actual customer order [13]. The positioning of the CODP has great implications for a company's manufacturing strategy, as different approaches to and methods for planning and control is needed upstream and downstream of this point. The position of the CODP is also used to classify the production environment. Vollmann, Berry, Whybark and Jacobs [9], Olhager [13], and Schönsleben [7] all use a classification that consists of four different manufacturing situations: Make-to-stock (MTS), Assemble-to-order (ATO), Make-to-order (MTO), and Engineer-to-order (ETO). Olhager [13] investigates the most important factors affecting the positioning of the CODP and divides them into the three categories: *market, product,* and *production characteristics.* Forward or backward shifting of the CODP to better correspond to these factors may give increased competitive advantage.

Knowing the importance of PPC on the manufacturing firm's performance and the importance of achieving a strategic fit of these methods inspired us to map and evaluate existing frameworks for mapping the planning environment and identify which variables that are of importance.

3 Existing Frameworks for Mapping the Planning Environment

Although frequently discussed, there is a lack of a clear definition of a 'planning environment'. Based on the literature findings, the following definition is proposed and used for this study: *'The production planning environment is the sum of internal and external variables that influence the production planning and control process'.* A planning environment is company-specific and normally differs from company to company [3].

Through the literature study, multiple frameworks for mapping the planning environment were identified. However, none are comprehensive enough to capture the many facets of PPC and their influencing variables. This study has mainly investigated frameworks by: Jonsson and Mattsson [6], Schönsleben [7], Lödding [11], and Olhager and Rudberg [14].

Jonsson and Mattsson [6] conducted a conceptual study and a survey of 84 Swedish manufacturers to examine the fit between the planning environment and production PPC methods. Jonsson and Mattsson [6] argue that the fit of PPC methods is dependent on characteristic features related to product, demand, and manufacturing processes. Of the examined frameworks, this framework consists of the most variables, 21 in total. This framework has been chosen as the basis for the development of the integrated framework. It has further been complemented with the three other frameworks to cover an even broader scope of variables. This approach is supported by Jonsson and Mattsson [6], which points out that a larger number of variables for mapping the planning environment, especially related to the manufacturing process and shop floor control, are of great value.

Schönsleben [7] argues that the choice of a suitable concept of PPC is dependent on characteristic features describing the *customer, product or product family, the logistics and production resources,* and *the production or procurement order*. Especially the category 'production or procurement order' includes variables not present in Jonsson and Mattsson [6]. Hence, including these variables expands the scope of mapping variables.

Lödding [11] presents a framework for mapping variables affecting the choice of manufacturing control methods. It does not include a categorization of the variables, and compared to both Jonsson and Mattsson [6] and Schönsleben [7], the number of variables is relatively low. Lödding's framework is focusing the production control part of PPC as opposed to the two previously mentioned frameworks, consisting of variables closer related to shop floor control. It thus complements Jonsson and Mattsson's [6] framework, which, as stated previously, has a need for more shop floor control related variables.

Olhager and Rudberg [14] develop a simple framework where they present the different PPC levels and define what they consider the most important variables for each level. This framework only consists of five variables, and although the majority of these five are already covered by the previously presented frameworks, it complements the development process and points out important variables.

A comparison of the frameworks examined in this paper shows that they are partly overlapping, but all of them have some unique mapping variables. Furthermore, the different frameworks use different categories for dividing the mapping variables. A brief summary of the investigated frameworks is presented in Table 1. Through using these findings, an integrated and more comprehensive framework can be developed. The development of the integrated framework is described in Chapter 4.

Table 1: Investigated frameworks

	Jonsson and Mattsson [6]	Schönsleben [7]	Lödding [11]	Olhager and Rudberg [14]
Categories	Product, demand, manufacturing process	Product, production resources, production/ procurement order	N/A	Product, market, process
No. of variables	21	16	8	5

4 Towards an Integrated Framework

Based on the previously published mapping frameworks mentioned in the previous section, variables were extracted and fitted into the integrated framework. In addition, to ease the use of the framework and make it more applicable for cross case studies, values were defined for each variable. These values represent the different states that each variable can have. Some of these were found in literature, while others were constructed for this framework. The framework consists of 30 variables, grouped into three categories. These are *product, market,* and *manufacturing process related*. This is a frequently used classification scheme, used by among others Olhager [13], Hill [15], and van Donk and van Doorne [16]. This chapter presents and describes the 30 different variables, and, where it is considered necessary, the different values of each variable are explained.

4.1 Product Related Variables

The *CODP placement* illustrates at which point in the value chain a product is linked to a specific customer order [13]. In the framework, four distinctive production environments are pointed out: ETO, MTO, ATO, and MTS. In this framework, these four production environments have been used to sort the values of the rest of the variables, such that typical ETO-characteristics can be found on the left, while typical MTS-characteristics can be found on the right, as these two represent the two ‘extremes’ of production environments. This is similar to Hill’s [15] ‘product-profiling concept’. The possible uses of this structure are discussed further in Chapter 6.

Level of customization refers to the extent in which the customer can specify the properties of the finished product [6]. Is it a standard product, are some specifications allowed, or is it a fully customer-specific product?

Product variety represents the number of different product variants the firm is able to deliver [6]. Companies that aim at delivering a large range of products tend to find it beneficial to put their

CODP upstream in the value chain, while companies with a narrow product range find it easier to go for a MTS strategy.

Bill-of-material (BOM) complexity represents how many levels we can find in a BOM for a typical product that the company is producing [6].

Product data accuracy is referring to the data accuracy in the BOM and the routing file [6]. The importance of this variable is illustrated by the fact that inaccuracies in the BOM may lead to differences between planned and actual material usage, while incorrect data in the routing file might lead to a sub-optimized shop floor layout.

Level of process planning is the extent of which detailed process planning, such as systematic determination of manufacturing operations and their sequences, is carried out prior to initiating the manufacturing of the product [6]. In the framework, this variable ranges from 'none', which illustrates a situation where they plan the production on-the-go, to a fully designed process where every operation is planned in detail before initiating production.

4.2 Market Related Variables

P/D ratio represents the ratio between accumulated production lead time (P) and the delivery lead time (D) required by the customer [6]. As emphasized by Olhager [13], this is one of the most important parameters to consider when deciding the CODP placement. Is the production lead time short enough to meet the customer requirement, or is a stock of finished goods required?

Demand type refers to the origin of the production orders. This could either be from forecasts, calculated requirements based on the company's safety stock policy, or actual customer orders [6, 7].

Source *of demand* indicates the origin of the sales order. Either it comes from a stock replenishment order (vendor managed inventory (VMI)) or an actual customer order [6].

Volume/frequency refers to the annual manufacturing volume and the frequency of which products are manufactured. The variable ranges from a few high-value customer orders per year, to a large number of customer orders per year. Another alternative is that customers place call-off orders based on the company's production and delivery schedules [6].

Frequency of customer demand is defined as the regularity of demand for a specific product. *Unique* refers to once within a specific observation period, typically a year. *Block-wise or sporadic* means multiple times within the period, but with no recognizable regularity. *Regular* indicates a regular demand, which can be calculated for each period using forecasting techniques. *Continuous* refers to a demand that is about the same in each observation period [7].

Time distributed demand refers to how detailed the calculated demand is. It can either be time distributed or simply given as an annual figure [6].

Demand characteristics says whether the demand is independent or dependent [6]. Independent demand is demand for a finished product, while dependent demand is defined as demand for components or sub-assemblies [17].

Type of procurement ordering indicates how supplies are procured. *Order by order procurement* refers to a situation where the company simply is ordering their calculated needs from a supplier, while *order releases from a delivery agreement* refers to an integrated solution where the company has established a delivery agreement with their suppliers regarding regular deliveries [6].

Inventory accuracy is defined as the accuracy of the stock on hand data [6]. Inaccuracies in stock data could be a result of poor discipline regarding keeping the stock data updated or poorly designed systems.

4.3 Manufacturing Process Related Variables

Manufacturing mix indicate, from a manufacturing process perspective, whether the products are considered homogenous or mixed [6]. Homogenous products require more or less the same production process, while mixed products have significant differences in processing needs.

Shop floor layout refers to how the shop floor is organized [6, 7, 11]. To differentiate, the typology by Slack, Chambers and Johnston [10] is used, which defines four types: *Fixed-position, functional, cell,* and *product layout.*

Type of production refers to the average size of the production run and how frequently these runs are repeated [7, 11]. Lödding [11] differentiates between four types: *single unit production, small series, serial production,* and *mass production*. Table 2 states the differences between these four.

Table 2: Four types of production [11]

One-time production	Small series	Serial production	Mass production
Small production runs	Size of production run < 50	Size of production run > 50	Very large production runs
No repetition	Number of repetitions < 12	Number of repetitions < 24	Continuous production

Throughput time refers to the typical throughput time in the production, i.e. the time spent for a product to go through the entire production [6]. This may range from hours up to years for some products.

Number of major operations represents the number of major operations in a typical production routing [6].

Batch size refers to the typical size of a production order [6]. For ETO, MTO, and ATO companies, the batch size is usually equivalent with the customer order quantity. For MTS companies, the batch size is usually measured relatively to the number of weeks of demand it covers.

Frequency of production order repetition is, within a time period, how often a production order for the same product is released [7].

Fluctuations of capacity requirements refer to how much the production capacity requirements vary. The capacity fluctuations are mainly due to fluctuations in customer demand, but are usually not as strong as the demand oscillations, since the use of safety stocks may mitigate this effect [11].

Planning points is the number of manufacturing resources that, from a production and capacity planning point of view, can be seen as one entity [14].

Set-up times refer to the typical time that is needed to prepare the manufacturing resources to perform the specific task [6, 14].

Sequencing dependency indicates whether the manufacturing set-up times are dependent on the manufacturing sequence [6]. Sequencing dependency might stem from the fact that some products can be produced with the same tooling, while others require different tooling.

Part flow refers to the transport of parts between workstations [11]. Four distinct types of part flow are outlined in the framework. *Bulk* refers to a situation where the entire batch is processed together. For *lot-wise flow*, smaller parts of the batch, i.e. lots, are transported and processed together. *Overlapped flow* refers to the case where an already processed portion of a lot is transported to the next workstation in order to keep up the utilization. The last type is *one-piece-flow* which means that the part is transported to the next workstation as soon as it has been processed [11].

Material flow complexity depicts the complexity of the material flow at the shop floor. The complexity increases with the number of different possible routings in the production, in addition to the optimization level of the production layout [11].

Capacity flexibility refers to which degree the company is able to adjust the production capacity and how quickly they can do it [11].

Load flexibility, on the other hand, refers to the possibility of adapting the load to the available capacity. This can, for instance, be done by shifting the start or end-date of an order, placing orders externally, or declining orders when capacities are fully booked [11].

5 Case Samples

As part of testing the framework, as well as initiating a cross-company research project, five manufacturing companies have been investigated. This includes a shipyard, a manufacturer of ship propulsion systems, a furniture manufacturer, a pipe manufacturer, and a manufacturer of underwater sensor systems. Because of the large differences regarding the product complexity, market requirements, and production processes, it is expected that there also will be significant differences in the planning environments. This hypothesis was tested through using the developed framework.

Kleven is a shipyard that produces both new vessels as well as offers service, repair, and rebuilding of all types of vessels. Their products have a very complex structure; the production lead times are long, and there is a lot of coordination required in the production.

Brunvoll produces thruster systems for ships. The products are mostly standard, but there are some adaptations to the thrusters depending on the customer requirements. These products have a highly complex structure, and they produce around 350 units a year.

Ekornes is a furniture producer that produces according to customer orders. They offer mass customization by providing the customer with choices regarding e.g. the color of their furniture. A large part of their production is manual labor.

Pipelife produces plastic pipe systems used for, among others, water, ventilation, and electrical purposes, which are standard products. Because of very strict required delivery times, they have to produce to stock. They have challenges with forecasting future demand, which leads to stock build-ups. In addition, the setup times in production are extensive, which means that they have to carefully balance batch size with responsiveness.

Kongsberg Maritime Subsea develops and produces underwater acoustic sensor systems used in underwater mapping, underwater navigation, and fishing. They produce standard products with some room for customer specifications. Because of the P/D ratio, where the required delivery lead time is considerably lower than the production lead time, products are made to stock. Of the major challenges in the current planning and control are long throughput times and high WIP levels. These issues are a consequence of the high product complexity and the high material flow complexity in the job shop environment.

The framework was filled out for each company through interviewing representatives with detailed knowledge of the company. Each variable was classified according to the proposed classification scheme in the framework. The results are presented in Table 3.

Table 3: Integrated framework for mapping the planning environment
***A:** Kleven, **B:** Brunvoll, **C:** Ekornes, **D:** Pipelife, **E:** Kongsberg Maritime Subsea*

<table>
<tr><th></th><th>Variable</th><th colspan="12">Values</th><th>Ref.</th></tr>
<tr><td rowspan="6">Product related</td><td>CODP placement</td><td colspan="3">ETO
A, B</td><td colspan="3">MTO
B, C</td><td colspan="3">ATO</td><td colspan="3">MTS
D, E</td><td>[6, 7]</td></tr>
<tr><td>Level of customization</td><td colspan="4">Fully customer specific
A</td><td colspan="4">Some specifications are allowed
B, C, E</td><td colspan="4">None
D</td><td>[6]</td></tr>
<tr><td>Product variety</td><td colspan="4">High
A, B, C, E</td><td colspan="4">Medium</td><td colspan="4">Low
D</td><td>[6, 11, 14]</td></tr>
<tr><td>BOM complexity</td><td colspan="3">More than 5 levels
A, E</td><td colspan="3">3-5 levels
B</td><td colspan="3">1-2 levels and several items
C</td><td colspan="3">1-2 levels and few items
D</td><td>[6, 7, 14]</td></tr>
<tr><td>Product data accuracy</td><td colspan="4">Low
A, B</td><td colspan="4">Medium
A, B, C</td><td colspan="4">High
C, D, E</td><td>[6]</td></tr>
<tr><td>Level of process planning</td><td colspan="4">None</td><td colspan="4">Partial process planning
A, C, E</td><td colspan="4">Fully designed process
B, D</td><td>[6]</td></tr>
<tr><td rowspan="9">Market related</td><td>P/D ratio</td><td colspan="4"><1
A, B, C</td><td colspan="4">1</td><td colspan="4">>1
D, E</td><td>[6]</td></tr>
<tr><td>Demand type</td><td colspan="4">Customer order allocation
A, B, C</td><td colspan="4">Calculated requirements</td><td colspan="4">Forecast
D, E</td><td>[6, 7]</td></tr>
<tr><td>Source of demand</td><td colspan="6">Customer order
A, B, C, D, E</td><td colspan="6">Stock replenishment order
D, E</td><td>[6]</td></tr>
<tr><td>Volume / frequency</td><td colspan="3">Few large customer orders per year
A, B</td><td colspan="3">Several customer orders with large quantities per year</td><td colspan="3">Large number of customer orders with medium quantities per year
C, D, E</td><td colspan="3">Frequent call-offs based on delivery schedules</td><td>[6, 14]</td></tr>
<tr><td>Frequency of customer demand</td><td colspan="3">Unique
A, B</td><td colspan="3">Block-wise or sporadic
B, C, E</td><td colspan="3">Regular
C, D, E</td><td colspan="3">Steady (continuous)</td><td>[7]</td></tr>
<tr><td>Time distributed demand</td><td colspan="6">Annual figure
A, B, E</td><td colspan="6">Time distributed
C, D</td><td>[6]</td></tr>
<tr><td>Demand characteristics (*)</td><td colspan="6">Dependent
B</td><td colspan="6">Independent
A, C, D, E</td><td>[6]</td></tr>
<tr><td>Type of procurement ordering (*)</td><td colspan="6">Order by order procurement
A, B, C, D, E</td><td colspan="6">Order releases from a delivery agreement
C, D</td><td>[6]</td></tr>
<tr><td>Inventory accuracy (*)</td><td colspan="4">Low</td><td colspan="4">Medium
A, B, C</td><td colspan="4">High
D, E</td><td>[6]</td></tr>
</table>

Table 3: Integrated framework for mapping the planning environment (continued)
***A:** Kleven, **B:** Brunvoll, **C:** Ekornes, **D:** Pipelife, **E:** Kongsberg Maritime Subsea*

	Variable	**Values**					**Ref.**
Manufacturing process related	Manufacturing mix	Mixed products **A, E**	Homogenous products **B, C, D**				[6]
	Shop floor layout	Fixed-position **A, B**	Functional **C, E**	Cell **B**	Product **D**		[6, 7, 10, 11]
	Type of production	Single unit production **A, B, E**	Small series **B, E**	Serial production **C**	Mass production **D**		[7, 11]
	Throughput time	Years **A**	Months **A, B, E**	Weeks **B, C**	Days **C, D**	Hours **D**	[6]
	Number of major operations	High **A, B, E**	Medium **C**	Low **D**			[6]
	Batch size	Equal to customer order quantities **A, B, C**	Small, equal to one week of demand **E**	Medium, equal to a few weeks of demand **D**	Large, equal to a month's demand or more **D**		[6]
	Frequency of production order repetition	Non-repetitive production **A**	Production with infrequent repetition **B**	Production with frequent repetition **C, D, E**			[7]
	Fluctuations of capacity req.	High	Medium **A, B, C, E**	Low **D**			[11]
	Planning points	High **A**	Medium **B, C, E**	Low **D**			[14]
	Set-up times	Low **C, E**	Medium **A, B**	High **D**			[6, 14]
	Sequencing dependency	None	Low **C, E**	Medium **A, B**	High **D**		[6]
	Part flow	One-Piece-Flow **A, B**	Overlapped **E**	Lot-Wise **B, C, D**	Bulk (Batch)		[11]
	Material flow complexity	High **A, E**	Medium **B, C**	Low **D**			[11]
	Capacity flexibility	High	Medium **C**	Low **A, B, D, E**			[11]
	Load flexibility	High **A**	Medium **B, C, E**	Low **D**			[11]

(*): Not dependent on production environment

6 Discussion

This paper presents an integrated framework for mapping a company's planning environment. This section discusses the causality between the variables, the difference between internal and external variables, as well as the different uses of this framework.

6.1 Causality of Variables

The framework presented 30 mapping variables, but there is undoubtedly some causality between a number of the variables. Based on a conceptual analysis of the different variables, an assessment has been made regarding the causality between the variables. This is based mainly on logical assumptions and can be seen as an initial hypothesis regarding how the variables interact. The causality between the variables is presented in Table 4. Two plusses indicate a strong causality, i.e. it is expected that the value of this variable strongly influences the value of the other. One plus implies a weaker, but still existing causality. For the rest, no direct causality is presumed, although it might be an indirect causality through other variables. The possible uses of this table are discussed in Section 6.3.

6.2 Internal and External Variables

Internal variables can be defined as variables that the company can adjust through altering their management system. External variables are given by the environment, and the company needs to adapt to these. Although some of the variables presented in the framework are influenced by external variables, few are purely external. The only variable that can be considered purely external is *frequency of customer demand.* Some might argue that this one can also be influenced, for instance through marketing initiatives, but in the end, it still remains out of the company's control.

6.3 Usage Areas

Common Reference Framework. The literature study uncovered several frameworks, but there are seemingly no preferred frameworks for investigating companies' planning environments. Agreeing on a common reference framework will increase rigor of future research within the field. It can, for instance, be a starting point to identify appropriate PPC methods for a particular environment.

Initial Screening. This framework can be used to do an initial screening of a manufacturing company and to get an overview of their planning environment. It presents straightforward variables that can be used as a comprehensive checklist in the mapping process. A mapping like this can thus also be used as a starting point for externals, such as consultants working with the company.

Table 4: Causality between the mapping variables.

		Variables																													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Influenced by	**1**						+		++									++	++			++			+						
	2	++		++	+	++		++	+	+	+	++	+				++	++	++			+	+	+	+			+	+		
	3	++				+					+	++	+				+	+	+			+	+	+							
	4	++				+															+				+						
	5	+														++															
	6																			+											
	7	++					+		+													+									++
	8						+															+									+
	9	+							+		+																				
	10	+																+	++			++		++							
	11	++									+		++					+	++				++								
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	25	++	+	+			+				+								+	++		++	+								
	26		+	+																						++					
	27																			++											
	28																														
	29	++	+																												
	30		+																												

Note: ++ Strong causality; + Weak causality; **Variables:** 1: CODP placement; 2: Level of customization; 3: Product variety; 4: BOM complexity; 5: Product data accuracy; 6: Level of process planning; 7: P/D ratio; 8: Demand type; 9: Source of demand; 10: Volume/frequency; 11: Frequency of customer demand; 12: Time distributed demand; 13: Demand characteristics; 14: Type of procurement ordering; 15: Inventory accuracy; 16: Manufacturing mix; 17: Shop floor layout; 18: Type of production; 19: Throughput time; 20: Number of major operations; 21: Batch size; 22: Frequency of production order repetition; 23: Fluctuations of capacity requirement; 24: Planning points; 25: Setup times; 26: Sequencing dependency; 27: Part flow; 28: Material flow complexity; 29: Capacity flexibility; 30: Load flexibility

Case Study Tool. Developed as a matrix, the framework allows for an easy arrangement of the collected data, detailed analysis, and cross case analysis [18]. While the standard values for each variable simplifies the cross case studies, it might be argued that the framework therefore is better for cross case analysis than for single case studies. However, the framework can easily be adapted to an in-depth single case study through making the values more exact, for instance by giving the exact number of product variants. Regarding the variables with high, medium, and low scales, the researcher should decide whether to rank these relatively among the cases or not. The benefit of ranking them relatively is that the researcher can highlight the differences between the cases to a larger degree, and the results are independent of the researcher's 'realm of experience' [19, p. 392]. The disadvantage of choosing this approach is that it makes the analysis inaccurate outside of the case sample, and the resulting company profiling cannot be used to evaluate the conformance between the variables.

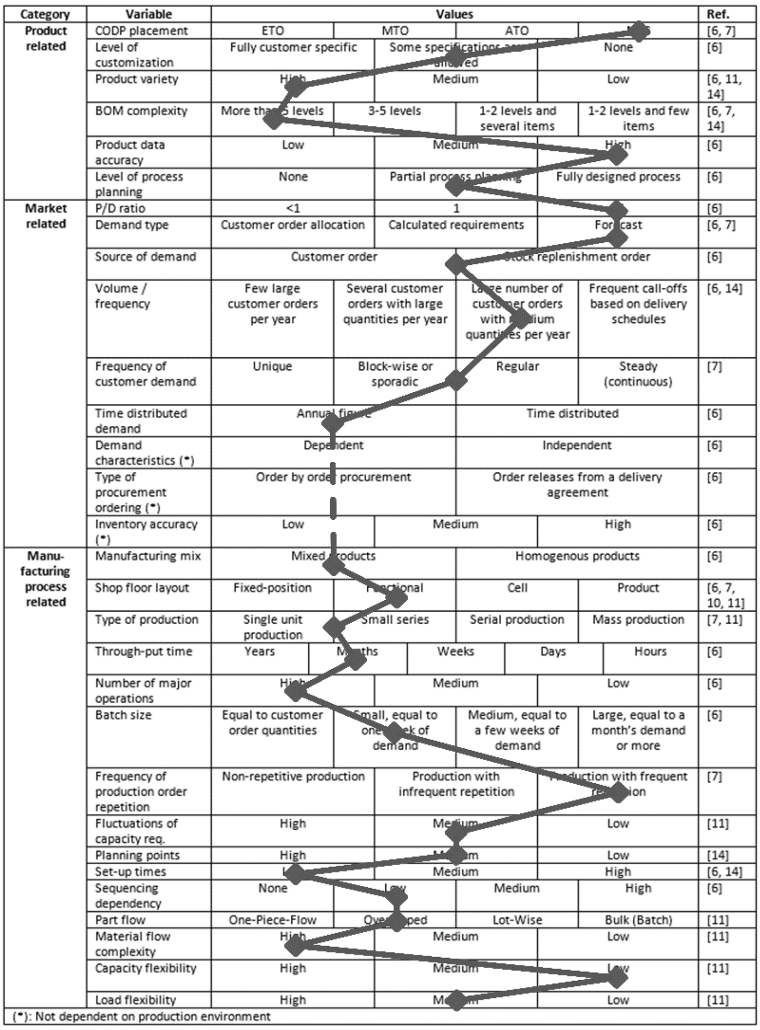
Benchmarking. By using the framework to map different companies, it will be easy to compare them and identify similarities and differences. This way, it could also be used as a benchmarking tool to compare against, for instance, a company that is considered 'best-in-class'. Through comparing the state of the variables, it is possible to uncover improvement areas.

Causality Effect. The causality matrix presented in Table 4 may be used as a decision support tool for change processes. For instance, if a company experiences that a variable suddenly changes state, either because of changes in their own structure or because of external influence, the matrix gives input on which other variables might be influenced and possibly also need to be adjusted to better conform to the new premises. As visible in the matrix, some variables are heavily influenced by other variables, while some are more or less independent.

Company Profiling. Because of interrelations between the variables, the framework is structured in a way that companies clearly should see a pattern, a so-called company profiling, when populating the framework. This is similar to Hill's [15] product profiling concept. As mentioned in Chapter 4, there are typical 'ETO characteristics' and 'MTS characteristics'. To some degree, the case study confirmed this. Companies that produce complex, customized products see that a majority of their variables correspond to the values on the left side in Table 3. On the other hand, companies that mass-produce standardized products find that their variables mostly correspond to values on the right side in Table 3. However, some of the variables are not considered to be dependent on the type of production environment. These are *demand characteristics, type of procurement ordering,* and *inventory accuracy*. These variables should therefore be ignored when using the framework as a profiling tool.

Briefly explained, the framework can be used to analyze the match between product and market characteristics and the manufacturing process choices. The resulting profiling will identify any mismatches and therefore highlight the areas that should be looked into for better conformance between the different groups of characteristics [15]. The framework can thus be used as a decision support tool. There are typically four ways to address a mismatch in the profiling [15]: The first alternative is to 'live with it' and continue as before. The second alternative is to alter the marketing strategy to ensure a better fit with the existing manufacturing process. The third alternative is to adjust and change the manufacturing process so that it, to a larger degree, matches the competitive priorities of the company. The fourth alternative is to go for a combination of the second and third alternative.

The majority of the investigated companies to a large degree follow the proposed profiling. As visible in the mapping, Kleven is a classic ETO company, while Pipelife, on the other hand, is a typical MTS company. The one who differs the most from the 'ideal' profiling was case company E, Kongsberg Maritime Subsea. This is a result of the fact that they produce highly complex products, typically associated with ETO and MTO companies, but the customers require such short delivery times that they find it necessary to produce to stock. This mismatch is easily spotted in their profiling (Fig. 1). The results can then be used to identify aspects that they should aim to alter. It should be noted, however, that the results should not be used 'blindly'. Taking examples from Fig. 1, even if a low setup time typically is associated with companies producing to orders, the deviation in profiling does not mean that the company should increase the setup time to better conform to MTS characteristics. It is rather an indication that, based on their setup time, the company might be responsive enough to produce based on customer orders.



Category	Variable	Values					Ref.
Product related	CODP placement	ETO	MTO	ATO	MTS		[6, 7]
	Level of customization	Fully customer specific	Some specifications are allowed	None			[6]
	Product variety	High	Medium	Low			[6, 11, 14]
	BOM complexity	More than 5 levels	3-5 levels	1-2 levels and several items	1-2 levels and few items		[6, 7, 14]
	Product data accuracy	Low	Medium	High			[6]
	Level of process planning	None	Partial process planning	Fully designed process			[6]
Market related	P/D ratio	<1	1	[illegible]			[6]
	Demand type	Customer order allocation	Calculated requirements	Forecast			[6, 7]
	Source of demand	Customer order	Stock replenishment order				[6]
	Volume / frequency	Few large customer orders per year	Several customer orders with large quantities per year	Large number of customer orders with medium quantities per year	Frequent call-offs based on delivery schedules		[6, 14]
	Frequency of customer demand	Unique	Block-wise or sporadic	Regular	Steady (continuous)		[7]
	Time distributed demand	Annual figure	Time distributed				[6]
	Demand characteristics (•)	Dependent	Independent				[6]
	Type of procurement ordering (•)	Order by order procurement	Order releases from a delivery agreement				[6]
	Inventory accuracy (•)	Low	Medium	High			[6]
Manu-facturing process related	Manufacturing mix	Mixed products	Homogenous products				[6]
	Shop floor layout	Fixed-position	Functional	Cell	Product		[6, 7, 10, 11]
	Type of production	Single unit production	Small series	Serial production	Mass production		[7, 11]
	Through-put time	Years	Months	Weeks	Days	Hours	[6]
	Number of major operations	High	Medium	Low			[6]
	Batch size	Equal to customer order quantities	Small, equal to one week of demand	Medium, equal to a few weeks of demand	Large, equal to a month's demand or more		[6]
	Frequency of production order repetition	Non-repetitive production	Production with infrequent repetition	Production with frequent repetition			[7]
	Fluctuations of capacity req.	High	Medium	Low			[11]
	Planning points	High	Medium	Low			[14]
	Set-up times	Low	Medium	High			[6, 14]
	Sequencing dependency	None	Low	Medium	High		[6]
	Part flow	One-Piece-Flow	Overlapped	Lot-Wise	Bulk (Batch)		[11]
	Material flow complexity	High	Medium	Low			[11]
	Capacity flexibility	High	Medium	Low			[11]
	Load flexibility	High	Medium	Low			[11]
(•): Not dependent on production environment							

Fig. 1: Profiling of Kongsberg Maritime Subsea.

7 Conclusion and Future Work

Through the literature findings, it became evident that there is a lack of an agreed upon framework for mapping planning environments, and there are disagreements regarding which variables should be investigated in order to get a comprehensive understanding of a firm's planning environment. This paper presents an integrated framework that can be used both as a mapping and decision support tool. It also investigates the causality between the variables, which no studies have done previously. Initial testing of the framework on five manufacturing companies shows that the framework is clearly able to highlight differences between these, while also highlighting variables that should be looked into to achieve better conformance between the variables.

Future research should examine whether it is beneficial to make the variables and their respective values more precise, especially keeping single case studies in mind, as this will give a more detailed mapping of planning environment. It may also reduce the bias when mapping the variables currently using scales of high, medium, and low. It should also be investigated how to use a mapping of a company's planning environment to determine appropriate PPC methods. Further, an assessment should be made whether the size of the framework can be reduced, for instance by discovering redundancy between variables. Lastly, the causality between the variables should be further investigated through large-scale empirical studies to see whether it supports the results from the conceptual analysis.

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Paper 3

Buer, S.V., Alfnes, E., Semini, M. & Strandhagen, J.O. (2019), “New insights on the relationship between lean manufacturing practices and type of production environment”, under review at *Production Planning & Control*.

Paper 4

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Paper 5

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Paper 6

Buer, S.V., Fragapane, G.I. & Strandhagen, J.O. (2018), “The Data-Driven Process Improvement Cycle: Using Digitalization for Continuous Improvement”, *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 1035-1040.

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The Data-Driven Process Improvement Cycle: Using Digitalization for Continuous Improvement

Sven-Vegard Buer, Giuseppe Ismael Fragapane, Jan Ola Strandhagen

Department of Mechanical and Industrial Engineering,
NTNU, Norwegian University of Science and Technology, Trondheim, Norway;
(e-mail:{sven.v.buer,giuseppe.fragapane,ola.strandhagen}@ntnu.no).

Abstract: Industry 4.0 is the first industrial revolution to be announced a priori, and there is thus a significant ambiguity surrounding the term and what it actually entails. This paper aims to clearly define digitalization, a key enabler of Industry 4.0, and illustrate how it can be used for improvement through proposing an improvement cycle and an associated digitalization typology. These tools can be used by organizations to guide improvement processes, focusing on the new possibilities introduced by the enormous amounts of data currently available. The usage of the tools is illustrated by presenting four scenarios from Kanban control, where each scenario is mapped according to their digitalization level.

Keywords: digitalization; digitization; Industry 4.0; improvement cycle; lean manufacturing

1 Introduction

In contrast with the three previous industrial revolutions, Industry 4.0 is the first to be announced a priori (Drath and Horch, 2014). Although a great opportunity to shape and optimize the solutions before they are fully released, the lack of empirical data makes the research highly theoretical and there are plenty of disagreements and differences in the literature regarding what Industry 4.0 is and what it consists of (Buer et al., 2018). Different perspectives in various studies have resulted in more than 100 different Industry 4.0 definitions in literature (Moeuf et al., 2017). New definitions of Industry 4.0 are proposed regularly, and large differences between these can be found both in semantics and in content. In general, definitions can change slightly over time. The need to propose new definitions and not conform partially or entirely to existing definitions leads to the assumption that there is still not a common opinion about Industry 4.0.

On the other hand, it might be too early to establish a definition of Industry 4.0. Although we can find pilot Industry 4.0 projects, some claim that we need to wait years, maybe even decades, before we will see “real” smart factories as envisioned by Industry 4.0 (Almada-Lobo, 2016, Bonekamp and Sure, 2015). Some ambiguity in concepts may also be valuable as it allows practitioners the flexibility to adapt the concept to fit a specific situation (Osigweh, 1989). Given the rapid speed in which Industry 4.0 is evolving, it can be argued that to define it now is pointless since it will merely be an image of a moving target, i.e. only valid at a certain point in time.

Nonetheless, this ambiguity in definitions makes it harder to align research in the area, as well as it makes it more complicated for practitioners to understand what Industry 4.0 entails and how to achieve this transition. The lack of a clear and agreed-upon definition will lead to empirical testing of an inexact and imprecise concept, and consequently, results from empirical testing make marginal contributions and prevent academic progress (Meredith, 1993, Shah and Ward, 2007). It is important for researchers within the field of Industry 4.0 to attack this ambiguity issue early and standardize the definition, converge the scope and synthesize the objectives of Industry 4.0. Hermann et al. (2016) emphasizes the current ambiguity surrounding the Industry 4.0 term and proposes four design principles guiding practitioners and scientists on how to approach Industry 4.0.

Pfohl et al. (2017) point out digitalization of processes and products as a key enabler of Industry 4.0. Others mention full digitalization as one of the core elements of Industry 4.0, enabling intelligent planning and control of production processes and networks (Erol et al., 2016). However, as with Industry 4.0, there is significant ambiguity in research regarding what digitalization entails, which steps that needs to be undertaken to get there, and how to measure the progress towards getting there.

To measure and evaluate processes within organizations, maturity models have been a popular tool among academics for numerous years, and are typically based on a pre-defined best-in-class description, with pre-described stages on the path towards reaching the top level (De Bruin et al., 2005, Wendler, 2012). Although a maturity model can be a useful tool in contexts where an end goal and best-in-class is clearly defined, it is problematic to use a maturity model in an emerging field because of the obvious ambiguity in what being best-in-class actually entails. Therefore, to develop a maturity model for digitalization is, in the best case, a qualified guess, heavily based on the researcher's perception of the ideal state.

This paper proposes to break the road towards improving processes through digitalization into five clearly defined steps, forming an improvement cycle. Employing this view avoids the possible bias issues mentioned above and provides a clear roadmap for moving towards a higher degree of digitalization of processes. This paper will introduce the proposed improvement cycle together with a digitalization typology to classify the different steps in the cycle. Following this, the usage of the cycle is demonstrated and the possible usage areas of this cycle are discussed.

2 Theoretical Background

2.1 Clarifying Digitization, Digitalization, and Digital Transformation

Following the predictions of Moore's law, hardware is now available with such processing power at such an affordable price that it enables the ubiquitous computing prophesied by Mark Weiser (1991). This aspect is one of the triggers for the trend of an increased level of ICT integration, popularly known as the "fourth industrial revolution". This is leading to a steep increase of research papers talking about terms as digitization, digitalization, and digital transformation. Some are using these terms interchangeably, while others claim there is a significant difference between the terms. This ambiguity confuses the reader, uncertain whether the author is seeing the terms as interchangeable or not. This paper aims to present definitions for these three concepts, central in the recent technological advances influencing all areas of business.

Schumacher et al. (2016) highlight some of the current confusion regarding the terms digitization and digitalization. Through a review of the literature, they argue that while digitization is about the conversion of analog signals into digital signals together with its storage and transfer, digitalization describes the effects, impacts, and consequences triggered by the availability of digital information. They thus consider digitalization and digital transformation as equivalent

(Schumacher et al., 2016), while other authors do not distinguish between digitization and digitalization (e.g. Kagermann, 2015, Leyh et al., 2016). Khan (2016) presents some of the disagreements in the literature regarding the clarification of digitization, digitalization, and digital transformation. We propose that there is a need to further distinguish these three terms. Precisely defining these terms supports the construct validity of research in this field. Based on the literature findings, we suggest these definitions:

- **Digitization:** The conversion from an analog format into a digital format.
- **Digitalization:** The use of digital data and technology to automate data handling and optimize processes.
- **Digital transformation:** Creating new business opportunities through the use of digital data and technology.

Fig. 1 further depicts the relationships between these three terms.

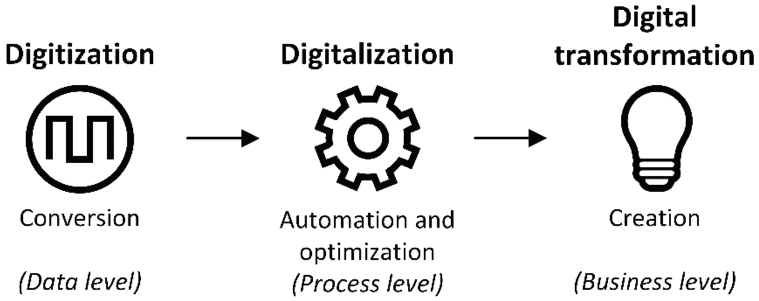


Fig. 1: Digitization, digitalization, and digital transformation (Adapted from Maltaverne, 2017)

A number of maturity models for digitalization and Industry 4.0 have been proposed the last few years. Examples include the System Integration Maturity Model Industry 4.0 (SIMMI 4.0) (Leyh et al., 2017) and the IoT Technological Maturity Assessment Scorecard by Jæger and Halse (2017). Both of these are to be used on an overall business level, and lacks proper empirical evidence of what characterizes best-in-class organizations. It is a significant gap between the high-level assessments in these models and the actual digitalization efforts that is needed to reach it. This paper proposes to measure specific processes in relation to how they use digitalization to improve their processes, through the use of an intuitive improvement cycle.

2.2 Improvement Cycles

Continuous improvement is essential for every organization aiming to stay competitive (Bicheno and Holweg, 2009). Improvement cycles gives a disciplined and structured framework for continuous improvement. Improvement cycles can be compared to control loops in industrial control systems, which continuously gather information to control processes towards a specific objective.

A number of improvement cycles have been proposed throughout the years: PDCA (Plan – Do – Check – Act), DMAIC (Define – Measure – Analyze – Improve – Control), IDEA (Investigate – Design – Execute – Adjust), 8D (Bicheno and Holweg, 2009), and RADAR (Sokovic et al., 2010) are some of the prominent examples.

Improvement cycles can be used as an overarching and standardized method to pursue improvement in organizations. Although seemingly simple, they are powerful tools and PDCA is considered a foundation of the Toyota Production System (Bicheno and Holweg, 2009).

3 Research Method

The research presented in this paper has used a conceptual research approach as presented by Meredith (1993). The work is motivated by existing literature and known challenges related to the recent trends of digitalization and Industry 4.0. The common features and opportunities presented by existing research have been adapted into an improvement cycle perspective through the use of philosophical conceptualization (Meredith, 1993).

4 The Data-Driven Process Improvement Cycle Explained

The competitiveness of today's business environments is constantly increasing, and the ability to continuously improve is a key success factor. As part of their quest to stay competitive, organizations have invested considerable sums into developing their digital infrastructure. ICT solutions can enable both cost savings and new business opportunities. As a "by-product" of these solutions, large amounts of unstructured data are created, which are often not used further for improvement purposes (Gantz and Reinsel, 2011). These unused data are typically known as "idle data" (Schmidt et al., 2015). Having large amounts of "idle data" has been indicated as an important part of implementing Industry 4.0 (Schmidt et al., 2015). Increased computing power has facilitated the possibilities of using big data analysis to discover patterns and improvement possibilities from datasets in which a human not necessarily would have found a pattern. This is the basis of every data-driven model. However, even if big data analysis is proven applicable in some cases, implementation is still scarce. This section introduces the data-driven process improvement cycle and relates it to the emerging trend of digitalization. This section introduces the five steps of the improvement cycle (Section 4.1), as well as the possible different states for each step (Section 4.2).

4.1 The Five Steps

Step 1 – Collection of data: You always need data to support your decision making. In general, data can be collected sporadic, periodic, or continuous. The data may appear in a physical or digital format, and may be collected with or without human intervention. Data can be obtained in different ways e.g. through measuring, counting, reading, or similar. The collected data give you information about today's situation and the current status of the key variables. It is thus assumed that you know what these key variables are and that sensors or other means of obtaining the data are organized for this purpose. This step obtains the data input and transforms it into shareable data.

Step 2 – Sharing: After the data is collected, it needs to be shared with the right actors that will process this data further. Data can be shared in different ways; ranging from paper-based documents between people to digital transmission between a machine and a cloud-based server. The basics of data sharing are the one-to-one exchanges of data between a sender and receiver. The technology advances in the recent years increased the possibilities of sharing data. Increased connectivity and data sharing velocity have led to a higher availability of data (Gantz and Reinsel, 2011, McAfee and Brynjolfsson, 2012). The sharing step describes in which way the data is exchanged between the different actors.

Step 3 – Analysis: The analysis step is concerned with the process of data inspection, cleaning, transforming, and modelling in order to discover useful information. Data inspection is the first quality control whether data can be read in the first place or not. Data cleaning checks the data for errors in terms of completeness. It detects and removes errors and inconsistencies from the data to improve the data quality (Rahm and Do, 2000). The data transformation part is an approach to find a deterministic mathematical function for each point in a dataset. Finally, data modelling analyzes data objects and their relationships to other data objects. It starts with the development of a conceptual model specifying how data relates to each other and is then transferred to a mathematical model (Rahm and Do, 2000).

Step 4 – Optimization: The optimization step is an adjustment process of changing a specified set of parameters to find an optimal or near-optimal solution without violating any restrictions (Rothlauf, 2011). The basis for the optimization process is the mathematical model established in Step 3. As the computer power has increased exponentially over the years, it is now possible to use more advanced optimization algorithms. With increased computational effort, the solution quality increases. Nevertheless, it is favorable for achieving fast results and response to use models that need low computational effort. The results of the optimization step are the basis for taking an improvement decision, which in the next step have to be integrated back into the system.

Step 5 – Feedback: Analyzing the collected data and discovering improvement possibilities is of no use if not fed back into the process. The results and information from the optimization step have to be transformed, shared, and implemented in order to ensure feedback to the process.

The data-driven process improvement cycle is illustrated in Fig. 2.

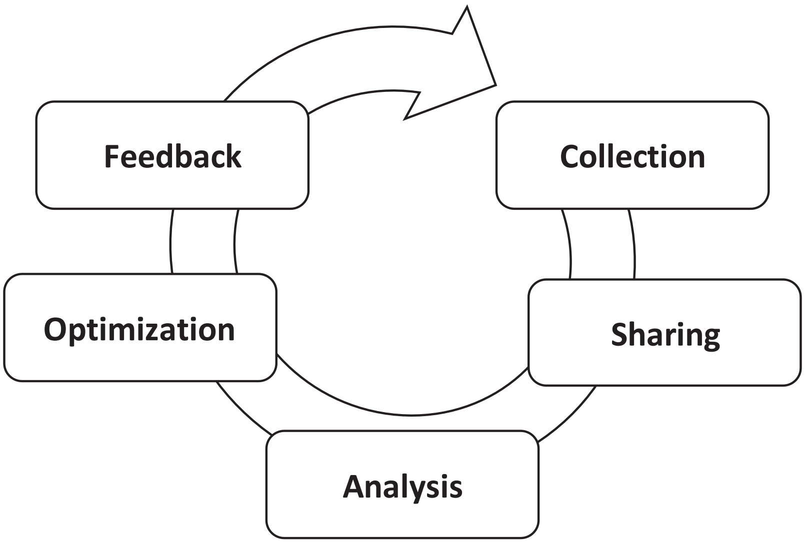


Fig. 2: The data-driven process improvement cycle

4.2 The Digitalization Typology

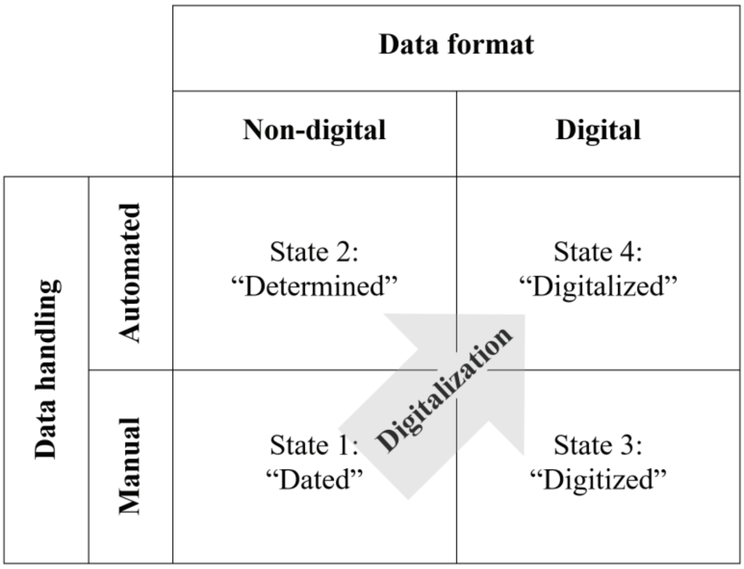
While industry traditionally has emphasized automating physical processes, the fourth industrial revolution focuses on automating informational processes and integrating these with physical processes through the use of cyber-physical systems (CPS) (Kagermann, 2015). CPS are "automated systems that enable connection of the operations of the physical reality with computing and communication infrastructures" (Jazdi, 2014, p. 1). Relating to the increasing degree of digitalized processes, every step in the improvement cycle can be mapped according to two dimensions: *data format* and *data handling*. The dimensions are summarized as a 2x2 matrix in Table 1.

Data format: Data is typically appearing in either digital or non-digital format. The obvious advantages of handling data in digital format are among other the increased flexibility, speed, and accessibility, together with reduced variable cost (Smith, 1999). On the other hand, a non-digital format also has some advantages, such as the ease of use and no proneness to system crashes.

Data handling: The cycle also differentiates on whether the step is undertaken manually or automatically. In manual operations, humans have a role in completing and ensuring the step is completed. If the step is fully automated and autonomous, no human intervention is required.

The two dimensions are illustrated in Table 1. Each of the steps in the improvement cycle can find themselves in one of these four states. State 1 represents traditional paper-based situations, characterized by a large proportion of manual data handling. State 2 might be effective but is inherently inflexible. State 3 has digitized the data flow, with the obvious benefits this entails, for instance related to cost, time, and flexibility. However, human intervention is still needed. State 4 represents a situation where the data is digital and handled automatically, which is a step towards enabling self-optimizing processes.

Table 1: Digitalization typology



		Data format	
		Non-digital	**Digital**
Data handling	**Automated**	State 2: "Determined"	State 4: "Digitalized"
	Manual	State 1: "Dated"	State 3: "Digitized"

4.3 Example – The Case of Kanban

This section will use the case of the well-known lean manufacturing tool Kanban as an example of how a management process can be mapped using the methods described in this paper. Kanban is used as a signal in pull production, signaling a workstation that they should supply materials to another workstation downstream in the process. We present four different Kanban-scenarios, each forming a separate level based on their digitalization maturity. This section briefly introduces each of the levels.

Level 1 – Traditional physical card-based Kanban: The Kanban system traditionally relies heavily on physical cards. Although these cards are intuitive and easy to understand, there are some issues and limitations with it. The ability to handle a large number of variants, the lack of flexibility, and the risk of losing the actual cards are among the challenges faced in traditional Kanban systems (Thoben et al., 2014). Relating it to the data-driven process improvement cycle, all five steps are thus executed both manually and the data is in a physical format. For most of the time, only the first two steps are undertaken, by collecting the data about materials that need replenishment, and then sharing this to the preceding workstation. Typically, this data is rarely used to complete the improvement cycle by analyzing the frequency of the Kanban signals and optimizing the number of Kanban cards and bin sizes.

Level 2 – e-Kanban: An electronic Kanban system, known as e-Kanban, is able to meet and handle some of the challenges typically associated with physical Kanban cards (Drickhamer, 2005, Thoben et al., 2014). Transmitting the Kanban signal electronically also makes it significantly more applicable for interplant deliveries. However, even if the system now is digital, the process of transmitting Kanbans is still manual. Typically, a human worker still has to manually inspect for when material replenishment is needed (collection) and then sending the Kanban, normally through scanning a barcode or entering it manually into the computer system (sharing). Analyzing and optimizing is also normally done manually.

Level 3 – Autonomous Kanban: Being able to automate the replenishment decision and the transmission of the Kanban signal will practically automate the Kanban loop (Hofmann and Rüsch, 2017). An industrial example of an autonomous Kanban system is the iBin system delivered by Würth presented in Kolberg et al. (2017). This bin automatically records the material level and sends it to the inventory control system. Based on this, orders are sent automatically to suppliers when needed (Kolberg et al., 2017). However, even if the Kanban loop is autonomous, it does not mean it is continuously improved automatically. The number of cards and bin sizes are still fixed, which might result in material shortages, or in the opposite case, materials might spend an excessive amount of time in intermediate inventories, halting endeavors to decrease throughput time.

Level 4 – Self-optimizing Kanban: Building on the autonomous Kanban system, a self-optimizing Kanban process is not only able to run the Kanban loop autonomously, but also use the collected data to analyze and prioritize improvements. A self-optimizing Kanban system autonomously adjusts the bin size as well as the number of cards in circulation according to predefined performance objectives, such as cost, throughput time, or similar.

Table 2: Comparison of the Kanban scenarios (see Table 1 for explanation of the different states)

	Collection	Sharing	Analysis	Optimization	Feedback
Level 1: Traditional Kanban	State 1	State 1	State 1	State 1	State 1
Level 2: e-Kanban	State 3	State 3	State 3	State 3	State 3
Level 3: Autonomous Kanban	State 4	State 4	State 3	State 3	State 3
Level 4: Self-optimizing Kanban	State 4	State 4	State 4	State 4	State 4

5 Discussion

We propose that organizations will reap the most benefit from digitalization when all five steps in the presented improvement cycle are both digital and automatic (State 4). Processes might be partly or fully digitized, but as long as the cycle is not completed automatically, the full potential of digitalization is not realized. Organizations can use the data-driven process improvement cycle as a part of their digital transformation. The data-driven process improvement cycle has relevance for both practitioners and scholars. This section outlines some of its possible usage areas.

Mapping and measurement of digitalization levels: As previously mentioned, there exists no established model on how the digitalization degree of a process can be measured. The data-driven process improvement cycle presents a simple approach to illustrate and measure an organization's efforts towards digitalizing their processes. The method highlights the importance of not digitizing and digitalizing just for the sake of it, but to focus these efforts towards actually improving processes. The data-driven process improvement cycle highlights that the digitalization efforts should be directed towards the five steps essential in any continuous improvement regime.

Guide to prioritizing improvements: Similar to maturity models, a process mapped according to the data-driven process improvement cycle clearly points out areas of improvements, in this case areas for increased levels of digitalization. It thus creates a process-specific roadmap towards digitalization. Similar to PDCA, it is used for individual processes, and organizations will find it beneficiary to develop an overall business framework to coordinate the individual improvement projects. It is also important to recognize the steps required to implementing new technologies, such as strategic planning, justification, training, and installation in addition to the actual implementation (Chan et al., 2001). The method presented in this paper is by itself not guiding how the digitalization transition should occur, merely pointing out the potential digitalization areas. This method may be used as part of a more overarching methodology for implementation of new technology, such as the APROS (Automation Project Selection) method (Alfnes et al., 2016).

Plan for improvement: An organization typically starts with an optimization goal in mind, such as increased productivity or reduced cost. The data-driven process improvement cycle provides an intuitive interface on how a system for continuous improvement of a specific variable can be designed. In these cases, the cycle should be gone through in the reverse direction, starting with specifying the optimization goals. Then an analysis process should be designed, specifying which data that should be collected in order to facilitate improvements. The lasts steps are to plan how data can be supplied and collected, respectively. This way of thinking could especially be useful for SMEs, whose limited financial resources forces organizations to pragmatically evaluate which data to collect. It is thus a "pull" way of thinking, asking for specific data, rather than "push", where you try to find improvement opportunities from whatever data supplied.

6 Conclusions

This paper introduced the data-driven process improvement cycle, a method for mapping and guiding digitalization efforts. It further highlights some of the differences in the literature regarding the definitions related to Industry 4.0 and presents some of the issues that this ambiguity might lead to. Furthermore, a clear distinction is made between digitization, digitalization, and digital transformation, which is useful to ensure construct validity in future research efforts within this domain.

The proposed improvement cycle differentiates itself from earlier improvement cycles in that it highlights the necessary steps for data-driven improvement efforts. It is universal in the way that it does not limit itself to specific digital technologies, but instead focuses on the functionality of the employed solutions regarding the data format and the degree of automated data handling. The presented examples from Kanban control illustrates how the tool can be used in practical situations.

The digitalization typology presented together with the improvement cycle can also be applied in other contexts, to classify the digitalization degree of process steps. The "plan for improvement" usage of the cycle also presents a novel and intuitive method for organizations to guide their digitalization efforts.

Future research efforts should focus on testing the model in empirical settings.

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