How to measure the impact of digital transformation along industrial value chains? – Cases of the semiconductor industry

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Abstract

This paper draws attention to the upcoming changes within sustainable supply and value chains of industries caused by innovative technology applications. With a special focus on investigating the digital transformation of semiconductor manufacturers, the presented study explores the scientific progress within this industry. A qualitative content analysis of several industrial use-cases from European semiconductor manufacturers was conducted. The results of this study contribute to theory building of how to evaluate value chain process improvement after innovative technical adaptations.

Keywords: Digital Transformation, Case Study Research, Value Chain Management

Introduction

In recent years, different industries have invested in an increasing number of activities to develop and explore new digital technologies to remain competitive in the digital transformed world. This affects different issues of core business processes such as the production processes, product development, organizational structures and supply chain management. To ensure the improvement of such processes it is of high interest to measure the impact of digitalisation. The semiconductor industry constitutes the main object of interest for the present study (ECSEL Austria, 2017). Based on the European project "SemI40" several use-cases were identified that deal with innovations to secure and support key technologies of electronic component manufacturing. These use-cases describe key activities to develop new solutions for improving manufacturing processes or support processes. In this study, we focus on the impact evaluation of these selected use-cases to gain new theories and to improve the industrial value chain by observing impacts on the economic, social and environmental dimension of operational sustainability. The Triple Bottom Line (TBL) approach serves as a fundamental instrument to observe the three dimensions of operational sustainability and progress (Elkington, 1998). For achieving the goals of the TBL dimensions and to generate a positive impact based on the integration of new technologies, it is crucial to measure the arising effects (Felsberger and Reiner, 2017, Seuring and Mueller, 2008). The need for scientific research in the field of digital transformation along industrial value chains leads to the following research questions:

- *RQ1: What are the expected economic (financial and non-financial), social, and environmental impacts of digitalized value chain management?*
- *RQ2: How does a technological shift influence the TBL dimensions and improve sustainable value chains?*

This paper is structured as follows: First, the theoretical background with respect to the impact of Industry 4.0 on sustainable value chain management (SVCM) is outlined. Afterwards we focus on the methodology, i.e. case study research, including case descriptions and research structure. Finally, the results of the case study research are presented and an outlook to future research directions is given.

Theoretical Foundations

Technology is forcing future manufacturing systems and the implementation of innovative technical solutions can help to secure a sustainable production environment. In recent years the increasing competition of European manufacturing companies has led to focus on optimization of operational activities to remain competitive against Asia and the US. Increasing demands in service requirements such as customizability and flexibility require improved operational processes (Barton and Thomas, 2009). The integration of intelligent and smart systems, digital technology adoptions and new management approaches in the context of Industry 4.0 is an emerging topic due to Value Chain Management. Our study aims to give answers to the underlying research questions and to identify future research directions based on the results of the case study analysis. In particular, we want to identify how different effects caused by a technological shift, improve the sustainable value chain of companies. Therefore, it is necessary to investigate the generated impact of such applications on the economy and society.

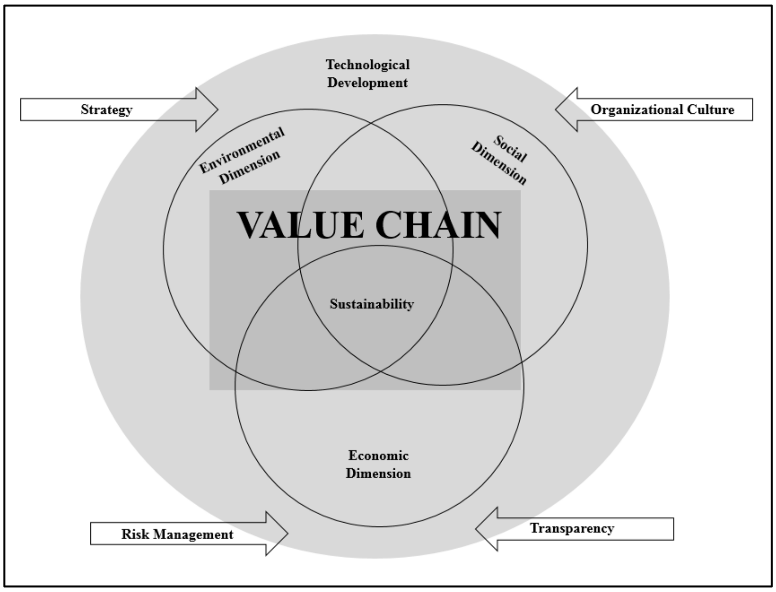

Figure 1: SVCM in a technological environment

The impact evaluation is crucial to justify future investments into Industry 4.0 management implications and research and development activities; moreover, to generate an outlook for upcoming challenges and changes *(RQ2)*. An interdependency between the social, economic and environmental dimension is at the core of sustainability. The approach serves as a fundamental instrument to observe these three dimensions of operational sustainability and progress (Elkington 1998). We use this approach as a framework to analyse different technical innovations in several application areas of the investigation area. In this paper, we extend the common TBL model by situational factors, characterized by technical aspects and situational/contextual factors affecting the decision variables (Carter and Rogers, 2008). Technological progress influences each of the three dimensions of sustainability. Figure 1. shows a representation of the integration of a fourth dimension: technological development. Technology has direct and indirect influences on sustainability across the whole value chain. Technological progress affects the whole organization and the pursued strategy of a business unit. Contextual factors such as the company strategy, the organizational culture, risk management and transparency influences the technological development and may gain retrospective impacts. New technical solutions or innovations can change the organizational culture or influence the overall companies strategy on a tactical as well as on an operational level. For example, a more flexible and secure communication between supply chain participants can enhance the transparency of the whole supply chain environment and may improve risk management. The results of our analysis show that the technological aspect is in the focus of the current research activities. Organizational sustainability and sustainable operations consists of these three core components - the economic, environmental and social performance (Gimenez et al., 2012). This research framework illustrates several research gaps in SVCM. One of these gaps exemplifies the interdependency between technology and sustainability. Furthermore, we want to underline the criticality to establish innovative, technical solutions in ongoing business operations to enhance operational benefits. Therefore, as a first step we analyzed seven industrial use-cases within a specific application area of the semiconductor industry by means of case study research. The main objective is to analyze the expected impacts of the use-cases. In this paper we focus on the implementation of smart factory technologies to enhance internal fab virtualization and digitalization.

Methodology

To give answers to the underlying research questions, we applied case study research based on an embedded design (Yin, 1994), which identifies a number of sub use cases within a specific application area of a semiconductor fab. In this regard, case study research serves to explore unstudied situations within the stated industry and suits as a promising methodology for developing new theories (Voss et al., 2002, Meredith, 1998). The method has unique strengths and therefore it is often used for developing new theories for examining unfamiliar situations (McCutcheon and Meredith, 1993). The methodology allows to understand how processes in organizations, teams and individuals unfold over time (Benbasat et al., 1987). The reason for applying case study research is referable to the fact that this methodology is a very common and impressive research method in operations management research, especially in the development of new theory (Voss et al., 2002). Within our research, based on several industrial use-cases, each case is dealing with a business-relevant challenge or problem of a selected industrial partner in the semiconductor industry concerning a specific set of manufacturing processes. In terms of case selection, we refer to the diverse-case method (Seawright and Gerring, 2008). The approach allows researchers to retain the holistic and meaningful characteristics of real-life events - such as individual life cycles, small group behavior, organizational and managerial processes, international relations, and the maturation of industries (Yin, 2009). For our purpose, case study research and qualitative content analysis of industrial use-cases serves for revealing problems and challenges related to impact evaluation of digitalized production processes. We conducted a cross case analysis of notable players in the European semiconductor industry. This article draws key aspects and principles of the case study research approach and compares insights of several cases of the semiconductor industry.

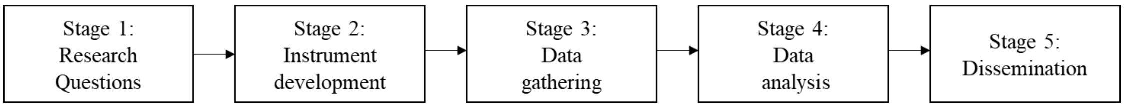

Figure 2: Stages in case study research
Based on Stuart et al., 2002

To structure our investigation we followed the concept by Stuart et al. (2002). Therefore, we used their five stages approach to classify our case study research (Figure 2). The first stage of the model handles the development of the research questions, followed by the second stage *"instrument development"* that deals with the selection of representative cases including their description and the development of the research instrument, that serves as a written guide to conduct further investigation. The third phase engages with the collection of required data by means of open, unstructured, semi-structured and structured expert interviews, focus-group discussions, analysis of documents and questionnaires. The data collected will be examined in the next step by using qualitative content analysis for extracting relevant information. Finally, the investigation is concluded with the documentation and dissemination of the results and the subsequent testing of internal, external validity and reliability (Stuart et al., 2002). Case research is essential where theory does not yet exist or is unlikely to apply.

Instrument development and case selection

The decision whether to use single, multiple, retrospective or longitudinal cases is dependent on the research aim and research questions (Voss et al., 2002). In our case study research, we investigate one specific application area including several use-cases. We named the application area "fab virtualization and digitalization". The use-cases are very complex as they represent highly automated and digitized industrial processes. However, the present study benefits from the fact that the cases are executed in a specific field of application within the semiconductor industry and are thus relatively homogeneous. Thereby, it is possible to explore challenges and opportunities by conducting a comprehensive analysis of the individual use-cases. This led us to follow multiple case study research to take the opportunity to study several contexts, demonstrated by use-cases, within the same investigated application area (Mukherjee et al., 2000). The problem is to define how many use-cases should be selected in order to generate similar outcomes which are likely to replicate or extend the emergent theory or to produce contrasting results but for predictable reasons. Typically, six to ten cases should be enough to achieve literal replication (Rowley, 2002). In order to differentiate between use-cases and case studies we refer to our colleagues of the SemI40 project. Rosenberger and Stocker (2018) described use cases as a description of a business-relevant challenge or problem of an industrial partner or "Enduser" concerning a specific manufacturing process or a specific set of manufacturing processes and support processes. Moreover, a use-case outlines the envisaged technical solution approach including the expected technical, social and economic benefits. Contrary, a case study is a documentation of how an industrial partner has solved a business relevant challenge by implementing a specific technical solution for a specific manufacturing process that besides includes the impacts on the three sustainability dimensions including the technological level (Rosenberger and Stocker, 2018). In our study, we have chosen seven use-cases, which are included in the research sample. The sample comprises different case study objects including different technological improvements such as autonomous guided vehicles, hybrid transportation systems, real-time visualization of Key Performance Indicators, implementation of sensors, monitoring of power consumption, visualization of transportation paths and the usage of simulations.

Introducing the cases

In this subsection, we outline the characteristics and background information of the case study sample (Table 1). The presented case description is based on the original documentation carried out by the "Virtual Vehicle Research Center" and was not modified by us. The industrial partners of the European project SemI40 (Infineon Technologies Dresden GmBH, Infineon Technologies Austria AG, Elmos Semiconductor AG and Robert Bosch GmbH) are responsible for the use-case description. We introduce each case by describing the industrial challenge and the envisaged solution. Afterwards, we set the focus on the case analyses to explore the expected impact behind the single use-cases. Out of the use-case documentation we were able to conduct detailed analyses.

Table 1: Case description

Case	*Description*
Case 1	Case 1 describes the implementation of mobile and autonomous vehicles to load and unload single manufacturing tools with production lots within a demonstrator environment. Further, the vehicles should interact with the MES to collect more reliable data. With the use of mobile robotic systems (autonomous guided vehicles) in transportation logistics, manufacturers in the semiconductor industry are trying to increase the degree of automation and throughput in production. Although different mobile robots are already used within production environments, these systems are mostly used within separated workspaces and do not work in parallel within the same areas.
Case 2	In the semiconductor production process, a wafer is transported from one manufacturing station to the next and is temporarily stored until its next processing step. Thereby, production machines can be located in different halls or on several floors of the same building. The transport of the wafers is usually performed by fully automatic rail-guided systems, which is the state-of-the-art solution. For interim storage the wafers are placed in shelves, so called "stockers" within the production area. To reach a higher automation level an alternative transportation system should be established, which in turn also allows to reduce the required intermediate storage areas. The establishment of a flexible hybrid transportation system to be controlled by the MES, combining elevator systems, rail-guided systems as well as autonomous mobile transportation robots is the overall objective of this use-case.
Case 3	Semiconductor fabs are monitored using a set of Key Performance Indicators (KPI). These indicators are based on historical data, while real-time information from the production facilities is hardly considered currently. The necessity to react to the market and customer needs in a flexible manner, however, requires fast and effective decisions. This leads to an increase of complexity in production. In a central IT-based manufacturing execution system (MES) all relevant information shall be accessible and presented in the form of production KPIs. Additionally, this system shall have the capability to trace back the existing KPIs to singular, causal events. With that, engineers and production managers shall be able to detect and understand dynamic relations within the process chains. Ultimately, quick and effective decision making processes shall be supported in this way. Tenable a real-time visualization of KPIs allows drilldown of process flows, product groups and production lots.
Case 4	Besides costs and time, effective quality assurance is one of the most relevant parameters for efficient manufacturing in the semiconductor industry. Until now detection and classification of quality issues was mostly done by especially skilled employees. Over the last years, the increasing level of fab automation asks for enhanced and fully automated quality controlling methods using extensive measuring instruments and tools. The implementation of the automatic control serves to overcome the limitations of the performance of a human operator in detecting defect items. A central IT platform has to capture and process quality data from a highly automated semiconductor manufacturing process in real time. On the basis of this data, especially trained employees will only have to check those wafers that have been flagged as defective.

Case 5	Case 5 handles the development of a high-performance monitoring approach to permanently monitor the power consumption of complex machines and supply systems. The production of semiconductor chips is associated with high energy expenditure. Thereby, high demands are imposed on constant temperature levels, humidity and purity. The energy demand within semiconductor fabs increases while energy prices themselves are rising as well. In global competition, manufacturing companies can achieve both ecological and economic benefits with increasing energy efficiency. Legal regulations force companies to concentrate even more on the sustainability of their production lines and their products. A high-performance monitoring approach is to be developed in order to be able to monitor the power consumption of complex machines and supply systems permanently.
Case 6	During ongoing production processes of a semiconductor production, lots are stored in shelves or transported on trolleys. Therefore, in non-automated areas or in areas with no potential for automation the transportation of lots on trolleys is done by human operators. A simulation is addressed to optimize production utilization and transportation paths. Therefore, transportation paths will be visualized on displays mounted on trolleys which are updated frequently. The system will help the operator to identify the relevant lots for the right destination placement faster.
Case 7	Case 7 has the target to remove an existing bottleneck in the transport system, which connects various facility levels and to optimize the placement of an additional floor-to-floor elevator by simulation. In the production environment, a transportation system takes over a majority of transportation jobs and connects different facility levels with a floor-to-floor elevator. Congestion at the elevator and related production delays can occur based on high utilization or is caused by maintenance work or technical faults. To omit this logistic bottleneck, an additional floor-to-floor elevator shall be installed. An optimally positioned additional floor-to-floor elevator removes a potential bottleneck and the associated material jams, stabilizes the transportation system even at high load and an enables an evenly balanced material flow.

Data gathering

Prior the actual data gathering, a template containing a questionnaire and a guided compendium was distributed to the industrial partners. The aim was to collect all relevant information regarding the use-cases of the project. Therefore, the partners had to describe the use-case in detail and the key exploitables from new processes, methods and innovations. In general, guided compendiums and questionnaires offer the opportunity to gain a lot of expert knowledge through specific questions related to an overall aimed topic. The template followed a standard form, including questions with respect to the envisaged technical solution of the task, the use-case related problem, the industrial challenge and the to-be situation. In detail, we addressed questions related to the expected social, economic and environmental impact of the solution, testing activity or envisaged innovation. We organized two face-to-face meetings in Graz and Klagenfurt and held several telephone conferences with HR & engineering experts located in Germany and Austria. The collection and description of the use-cases were conducted from September 2016 to October 2017 and were documented and updated with the permission of the industrial project partners.

Data analysis

The data analysis was initiated with the qualitative content analysis of the documents and use-case descriptions. To increase the rigor of the content analysis process we asked our partners to check the results of the filtered descriptions for incorrect formulations and wrong interpretation of their formulations. Afterwards we developed a use-case analysis table were the seven use-cases of the application area “internal fab virtualization and digitalization” are coded and filtered. The results were divided into four categories. The first category describes the current situation of the process to be improved. The second category deals with the industrial challenge of the use-case owner or the industrial partner. The industrial challenge describes the requirement that is posed to the new solution approach. The third category illustrates the description of the new solution or approach on a technological or process level (Rosenberger and Stocker, 2017). The last step of the analysis comprises the documentation of the expected impact. In doing so, we adhered to the TBL evaluation framework and evaluated the individual cases based on their impact on the three dimensions of sustainability i.e., the economic, social and environmental dimension (Felsberger and Reiner, 2017).

Findings

Challenges in application area

The qualitative analysis of the collected use-case data resulted in the identification of different challenges mentioned by the industrial partners (Table 2.). The challenges within this application area relate to the respective technical solution and are therefore not overall homogenous. We were able to identify three main categories i.e. autonomous transportation or fab logistics, improvement of production processes such as quality assurance processes and big data issues such as real-time visualization of data to make KPI´s better visible. Due to this, we analyzed the economic, social and environmental impact of the dedicated use-cases within the fab.

Table 2: Results of the qualitative content analysis

TBL-area	*Case1*	*Case 2*	*Case 3*	*Case 4*	*Case 5*	*Case 6*	*Case 7*
Economic	Decrease of lead time, increase of productivity, increase of throughput rate, increase of automation & productivity	Improved in-house logistics (distance, storage, different shop floors), controlled via MES, efficient use of production area	Real time visualization, improved automation strategy, improved preventive maintenance, SPC and control of production process	Timely quality data recording, decrease of production costs, elimination of destructive test methods, more digital quality data, improvements in subsequent processes (arrival rate, lead time, variability)	Decrease of production and material costs, increase of energy efficiency, energy costs	Optimization of transportation, avoiding stand-by times of equipment, improvements in production process (arrival rate, throughput, variability)	Decrease of bottlenecks, increase of arrival rate, better lead time
Social	Support of employee by mobile robots, assisting technologies	-	Multidisciplinarity of employees, secure work stations, decrease of monotonous activities	More satisfying job activities, decrease of monotonous activities, change of skill-set, improve of decision support	Eco-friendly visibility entails a more employees belonging work place	Assistance of employees by JIT changes, visual assistance for employees	Reduction of administrative work, improved decision support
Environmental	-	-	-	Efficient use of raw material	Competitive advantage by acquisition of sustainability and environmental certifications, reduction of CO^2 emissions,	-	-

Economic dimension

Most of the use cases handle with production process improvements. Therefore, we were able to identify some overlaps concerning the economic impact when comparing the cases with each other. Assessing the supply chain of an organization, several impacts through single process improvements are evident. Not only internal but also external improvements can occur. The investigated use-cases (Table 2) show that the enhancement of production processes has direct impacts on the manufacturing and sourcing part of the supply chain. For example, the early and precise detection of faulty items results into better information for the upstream and downstream departments of the company. The reduction of lead-time allows operating departments to give crucial information of demand forecasting to the sourcing department. Due to improved forecasts, the company may be able to change the manufacturing process from make-to-stock to a make-to-order strategy (Jamernegg and Reiner, 2007). The company can react faster to uncertainty of order fulfilments and give adequate information to the customer, which results in better service performance and customer satisfaction. Another impact will be on costs. The company can reduce operating and production costs if the inspection and fault detection operations are improved.

Social dimension

Semiconductor plants will need more experts and qualified engineers in specific fields and digitalization will lead to an increase of know-how and competencies. Multidisciplinarity will become more important. New job models and functions will emerge and companies have to set up new educational measures. Another aspect raised by analyzing several comments of human resource experts was the impact on social skills, e.g. the change of interpersonal contact, less human-to-human communication, impact on work satisfaction, different employment structures and the use of assistance systems. Preventive maintenance might trigger implications regarding the flexibility of the organizational structure as well as for the working time model, that reduces again costs and serves as a compensatory for time-off. The time interval employees maintain the machines will change i.e. the maintenance is forwarded to the standby times of the production lines. In terms of improved process control, the manual revision of false alarms is a very challenging work and should be reduced. Expensive engineering hours to rearrange the program in the production process will be reduced. The use of mobile robots supports the operators regarding physical liability, or may even free from physically demanding tasks. With the introduction of image recognition tools, the exhausting and monotonous control activities of employees previously responsible for manual inspection are changing to a more varied and thus more satisfying activity.

Environmental dimension

In semiconductor manufacturing, energy is required to process the silicon wafers in the production line. To run process equipment and tools in a semiconductor facility 40-50 per cent of the total energy consumption is needed. For improving energy efficiency at production level, there are several sustainable practices, which can be adopted by utilization of IoT technology (e.g. avoid peak time, integrate energy data in production schedule or automation of environmental controls) (Miragliotta and Shrouf, 2012). For this purpose, the energy consumption in the individual semiconductor manufacturing plant must be measured and the relevant energy flows must be understood. Production costs can be reduced by applying more energy-efficient manufacturing systems. This leads to price advantages against competitors and strengthens the competitiveness of companies. By acquiring sustainability and environmental certifications, own products will also differ from those of competitors. Modern production equipment and optimally operated machines will emit fewer pollutants and deal more carefully with limited resources in order to protect the environment. Another effect of these technical innovations is the continuous improvement of resource productivity and efficiency along companies' value chains. An increase of raw materials and energy prices and a simultaneous decrease of resource availability lead to bottlenecks in the productivity. The resource dependence of Europe from other countries is a problem concerning the competitive advantage for the future development (Marre et al., 2015).

Conclusion and outlook

Our study gives answers to the underlying research questions and identifies future research directions based on the results of the qualitative content analysis. The scientific contributions are relevant in order to highlight the evaluation of value chain process improvements due to innovative technical adoptions. In particular, we identify how a technological shift may influence the dynamical interaction along the digital transformed value chain under consideration of the dynamic dependencies between the dimensions of the TBL model i.e. the effect of smart factories on production workers, the organization, the fab and the supply chain. For our research work, we extend the common TBL model by situational factors that are characterized by technical aspects (Barrat et al., 2011). The results pave the way for integration of the digital transformation and process improvements to increase the competitiveness of manufacturing companies in Europe. Furthermore, investigations in terms of modeling value chain processes will lead to promising results that satisfy the reliability and validity requirements through research triangulation. It is expected to identify performance measures and indicators, which capture the sustainable development along the whole value chain as well as the performance impact of the digital transformation and integration of value chain processes.

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