Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 67 (2018) 386 – 391

www.elsevier.com/locate/procedia

11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME'17

A conceptual model for developing a smart process control system

Dennis Weihrauch[a,*], Paul Anton Schindler[a], Wilfried Sihn[a,b]

[a]Fraunhofer Austria Research Gmbh, Theresianumgasse 7, 1040 Wien, Austria
[b]Institute of Management Sience, TU Wien, Theresianumgasse 27, 1040 Wien, Austria

* Corresponding author. Tel.: +43 676 888 616 31, *E-mail address:* dennis.weihrauch@fraunhofer.at

Abstract

Current Manufacturing Execution Systems (MES) are not supporting a full integration into overall processes across the supply chain. Thus, optimization is limited to single areas. The SemI40 project is aimed at developing an integrated concept of Smart Process Control System (SPCS), which enhances the overall agility and productivity. The system, therefore, autonomously acquires and interprets process data to allow product individual optimization and enhancing logistics management. It also provides full traceability across the supply chain in real-time and allows model based process simulation and decision making support. The concept is developed based on requirements elicitation in cooperation with industry partners and combines state-of-the-art technologies with current trends, like vertical integration, big data and machine learning.

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Manufacturing execution system; Smart process control; Requirements analysis; Decision support

1. Introduction

Today's manufacturing industry is concentrated on value creation, based on existing production processes and interconnected digital technologies [1]. In modern production companies, Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES) and Advanced Planning Systems (APS) are pillars of IT architecture [2]. Nevertheless, digital transformation has reached the manufacturing industry [3], and there are high expectations on Cyber-Physical Production Systems (CPPS) [4]. While its short-term impact is often overestimated, its long-term impact tends to be underestimated [3].

In this paper, we describe a conceptual model for developing a Smart Process Control System (SPCS), which has been developed within the ECSEL JU project SemI40 [5]. It reflects the impact of the current digital transformation on the application of MES in the context of the semi-conductor industry. In chapter 2, we introduce ten MES general functions that are described in VDI standard for MES [6]. We use these functions to structure our requirements analysis in chapter 3. In order to capture requirements from five semi-conductor companies, we have applied methods of requirements engineering [7] and value stream mapping [8, 9, 10]. In chapter 4, we use the results to create the conceptual model, including a conceptual design of a Decision Support System (DSS) [11, 12, 13]. Chapter 5 discusses the key findings, limitations, applicability and transferability of the integrated approach to other industry sectors. Finally, we conclude and present future research work, in which the focus is placed on how our results can be used in the further course of the SemI40 project (cf. chapter 6).

2. Background: MES general functions

A MES aims to plan and manage manufacturing processes in semi- or even in real-time [2]. It guarantees transparency over processes, as well as information and material flows within the supply-chain [6]. The MES acts in addition to ERP systems, which focus on mid- or long-term goals and a higher company level [2]. According to [6], a state-of-the-art MES contains the following functions:

- *Order management* is a central component within a MES. Usually, an order is the trigger for activities in manufacturing. It contains data that is required for or

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2017.12.230

generated during the processing of the order. Various order types reflect the different production steps, like mechanical manufacturing, assembly or maintenance.

- *Detailed scheduling and process control* supports the processing of orders. It considers the availability of resources, like materials, manufacturing systems and work force, and sets them into a chronological order. Besides its focus on planning of manufacturing sequences, it must be able to react on unexpected events in semi- or even in real-time.
- *Equipment management* secures the availability, functionality and reliability of equipment and utilities, and so supports the maintenance process. It can be divided into machines and manual workplaces, tools and supporting equipment, and immaterial operating resources, like Numerical Control (NC) programs.
- *Material management* organizes the appropriate supply and disposal of materials for manufacturing. It especially manages work in process (WIP) goods, e.g. raw materials, semi-finished goods and final products, when they leave an inventory-managed stock.
- *Human resources management* provides the required personnel with the right qualifications and competences. It considers individual data of single persons or groups, like working time, shift plan and time accounts. Besides real-time applications, it is used for capacity planning and historical analysis.
- *Data acquisition* captures and processes event-driven information, like operating and machine data, as well as records of process, quality and personnel. Data transfer and capture can be automated, semi-automatic (e.g. scanner) and/or manual (e.g. typing).
- *Performance analysis* creates control loops to correct operational deviations (short-term) and to optimize and qualify processes (long-term). It enables the creation of reports and Key Performance Indicators (KPIs), comparing expected with real-time data, as well as DSS. It also takes care of process and product improvements, as well as root-cause analysis, enabled by performance and data analysis.
- *Quality management* secures and improves product and process quality. It covers (advanced) quality planning, quality control, gauge and complaint management. It can immediately react to quality issues, which can lead to an adaptation of manufacturing orders or processes.
- *Information management* integrates other MES functions in order to enable the processing of manufacturing processes and their optimization. It distributes and provides required information and can influence and control processes in manufacturing. It enables the allocation of order and resource data to process parameters. It also provides required information for tracking and tracing, as well as specific documents for the corresponding manufacturing step.
- *Energy management* plans, monitors and controls the energy consumption within manufacturing in order to reduce it. It creates transparency and supports an energy-efficient production. Targets can be economically or ecologically, e.g. a reduction of the total energy consumption, an increase of the energy efficiency or energy recovery.

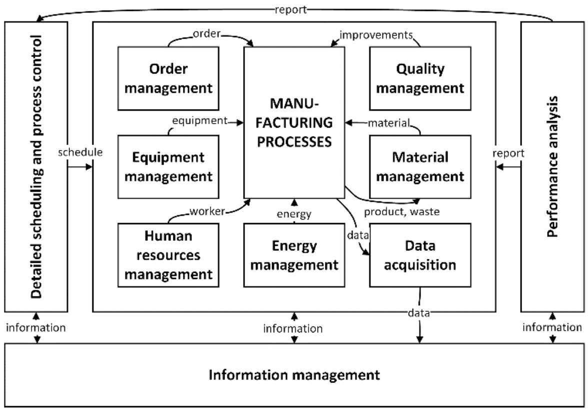

Fig. 1. MES general functions.

Figure 1 shows the correlation between the described MES functions and manufacturing processes. The inner functions interact directly with the processes, whereas the outer ones interact indirectly via the inner functions. The importance of information management will increase in the future with progressing digitalization [3], because it connects all other functions with each other.

3. Requirements from industry partners

In order to create a conceptual model for developing a SPCS, we identified and compiled requirements from five semi-conductor companies. To get a comparable view on the same level of detail and functional category, we designed a questionnaire. The companies were asked to describe their current and their target implementation of the ten general MES functions, listed in chapter 2. The answers have been evaluated by assigning a score, ranging from 0 (no implementation) to 4 (beyond state-of-the art). Afterwards, the results were processed by the requirements engineering team and have been presented in Table 1.

Energy management, human resource management and performance analysis are currently the functions with the lowest score. Mostly, they are implemented using independent software solutions with no automated interface to the MES. In contrast, data acquisition is implemented most sophistically, followed by material management. This is reflecting the typical situation in the semi-conductor industry with high quantities and required knowledge of a single product and related processes. The highest need for a future improvement is on equipment management (+1.8), detailed scheduling and process control (+1.6), as well as human resource management (+1.4). In general, the planned developments are going in the direction of automation, i.e. either creating interfaces between separate tools or integrating them into one.

Table 1. Current and target implementation of MES functions in five semi-conductor companies, evaluation in points from 0 (no implementation) to 4 (beyond state-of-the-art), average scores

MES general function	Current implementation	Target implementation	Change
Order management	1.6	2.8	+1.2
Detailed scheduling and process control	1.6	3.2	+1.6
Equipment management	1.4	3.2	+1.8
Material management	1.8	2.8	+1.0
Human resources management	0.6	2.0	+1.4
Data acquisition	2.4	3.2	+0.8
Performance analysis	1.0	2.0	+1.0
Quality management	1.6	2.6	+1.0
Information management	1.2	2.0	+0.8
Energy management	0.0	0.2	+0.2

In addition to this general evaluation, we conducted several on-site workshops and observations together with three of the companies. Therein, we analyzed their production, planning and scheduling processes by recording value streams under consideration of the activity, material and information flows [9]. As a result, we identified several improvement potentials that lead to the requirements listed in Table 2.

Table 2. MES requirements, identified in observations and value stream analyses of the manufacturing processes of three semi-conductor companies

No	Description
R1	The system shall calculate cycle times in real-time, considering changing production parameters.
R2	The system shall analyze the performance of equipment in real-time and provide specific KPIs in an aggregated format.
R3	The system shall trace products, record their exact location on the carrier (wafer) and link relevant process and quality data to it.
R4	The system shall support the decision making process by identifying events that occur within the manufacturing process, simulating their effects and proposing choices to the user.
R5	The system shall create quality control plans semi-automatically, based on the product definition and configuration.
R6	The system shall allow a dynamic adjustment of detailed planning in case of unexpected events.
R7	The system shall support a predictive maintenance process by the usage of statistical process control charts.

4. Conceptual model for developing a SPCS

We used the previous requirements to specify required features and build up our conceptual model for developing a SPCS. It consists of four main features, listed in Table 3, which are described in the subsequent sub-chapters.

Table 3. Definition of SPCS features

No	Description
F1	Live virtual representation of the manufacturing process
F2	Providing access to past manufacturing and quality records
F3	Simulation and prediction of future states in manufacturing
F4	Supporting decision making activities

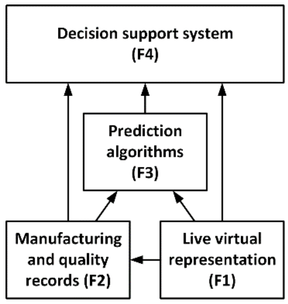

Fig. 2. Correlations between the defined SPCS features.

Figure 2 depicts the correlations between the aforementioned features. Data from the live virtual representation (F1) is used to generate manufacturing and quality records (F2). Algorithms for simulation and prediction of future states (F3) use data from (F1) and (F2) to determine possible effects of events or decisions. The DSS (F4) finally uses data from all sources (F1-F3) to provide a holistic view of the current situation, past events and possible future developments.

4.1. Live virtual representation of the manufacturing process (F1)

The SPCS shall provide a live virtual representation of the manufacturing processes, i.e. it should reflect the real states and processes that are currently existent in production. It includes objects, like orders, raw materials and products, equipment, the transport systems, processes, etc. Figure 3 shows an exemplary presentation of a set of manufacturing processes.

Production starts at the left inventory with a transport order. The grey arrow routes the semi-finished product via the transportation system to process A. The grey bar below indicates the filling level of the entrance queue. Process A consumes the manufacturing order, the required equipment, energy, raw material and workforce. It improves the product, generates process data, and creates waste material. Then, the processed semi-finished product is forwarded to the subsequent processes, until it reaches the inventory at the right. In the example of Figure 3, process B is in a critical state. An event has caused its shutdown and disturbances in the production process. Products and materials have to be rerouted to the parallel process D, which affects other products as well. Then, the product flow is separated and goes to the two parallel processes C and E. Finally, the product arrives at the inventory at the right.

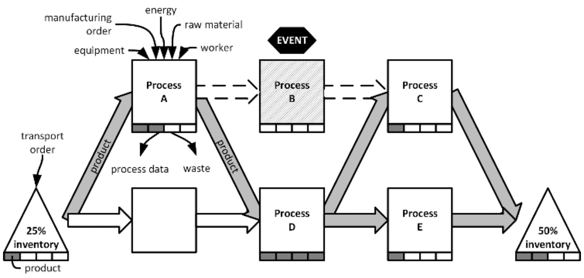

Fig. 3. Live virtual representation of the manufacturing process.

In order to create such a live virtual representation of the production process, real-time data of the related objects (e.g. products, equipment or processes) is required. Sensors, distributed across production, capture the location of every product, raw materials, equipment and transport system. Process parameters and quality data are recorded along manufacturing and stored within a database. The desired implementation level determines which data has to be recorded and depends on the use case. As a result, we have identified the following benefits:

- A real-time tracking of products is possible, which can be used to reduce searching time in production.
- Transparency in production is increased, in particular the view on the availability of critical parts.
- Suppliers can be given a more accurate picture of when a part is required and what is the consequence if it not comes at the right time.
- Customers can be updated about the production process and when they can expect their products.
- Events that could cause a disturbance can be identified faster and so allow an immediate reaction to minimize their negative impact.

4.2. Providing access to past manufacturing and quality records (F2)

The SPCS shall record data sets from the live virtual representation of the production process in specific intervals. The size of the interval defines how often a snapshot is made and can be specific for a type of data. The system can then analyze the recorded data in order to optimize the production processes. Algorithms can run constantly in the background searching for already known patterns or help users to generate reports, like evaluating the dependence of the energy consumption from the production program for the last year. Machine learning algorithms could also be applied to increase the extent and quality of the results [14]. At this stage, we have identified the following benefits:

- Upstream and downstream traceability of products is enabled, including records about the product's location, related process parameters and quality data.
- Predictive maintenance is supported, which brings down maintenance costs and disturbances of the production process.
- Recurring problems and their root causes can be identified and consequently solved in order to optimize the production process in detail or as a whole.

4.3. Simulation and prediction of future states in manufacturing (F3)

The SPCS shall be able to simulate and predict the production process based on the current live virtual representation and past records. In order to simulate future states, a model of the production system needs to be created. In order to predict future states, statistical analysis of records, combined with a self-learning algorithm can be used. Depending on the use case and type of data, an appropriate approach will be employed. Scenarios with a simplified data set and strict constraints can be evaluated against a set of KPIs in order to determine the overall quality of each solution. The following benefits have been identified:

- Cycle time calculation [15] for specific products or orders is enabled. This allows an improved production planning and knowing exact delivery dates for customers in case of order changes or unexpected events.
- Prediction of future capacities demands and bottlenecks is enabled.
- Prediction of recurring events with a negative impact is enabled and allows counteracting in advance.

4.4. Supporting decision making activities (F4)

The SPCS shall support the decision making process. Information is the foundation of a robust decision making process and is required to react effectively on events [11, 16]. An event can be anything that affects the process, e.g. an order modification by a customer, an unexpected energy shortage or a scheduled maintenance of a machine. A decision making process requires:

- A complete picture of the current situation in manufacturing to understand the event and its context.
- Records of the past manufacturing process, as well as data about previously occurred events.
- A tool to simulate or predict the effect of an event or a decision within definable what-if scenarios.

Figure 4 shows a flow chart of a DSS. The DSS monitors the production system constantly and is searching for events. If an event has been identified, the system analyzes it and tries to identify the root cause(s). In the next step, it simulates or predicts the effects of the event. If there is a significant effect on the production system, possible choices (decision alternatives) are identified. Then, the DSS simulates or predicts their effects on the production system. If the effect is minor (below a specifically defined threshold), decision making could be automated. If the effect is major, the DSS proposes preselected choices, including their simulated effects. The user selects one of the decision alternatives or defines a new one. Finally, the decision is implemented by the system.

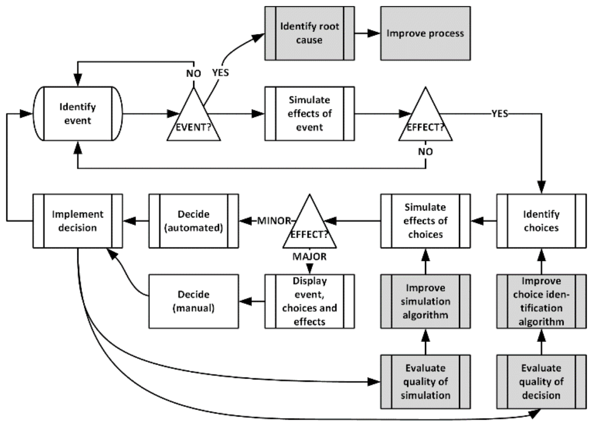

Fig. 4. DSS flow chart.

In this case, we identified the following benefits:

- A formalized and supported decision making process, which leads to a better understanding of connections in production and finally to better and faster decisions.
- The identification of root causes is supported.
- The simulated or predicted effects show the impact induced by a decision and can evaluate the quality of a decision.
- Machine learning algorithms can be used to improve the simulation and prediction and lead to better decisions in the future.

5. Discussion

Hereafter, we discuss our key findings and limitations within the requirements analysis phase and in relation to the SPCS conceptual model. Subsequently, we present current developments in integration and decentralization of IT architecture and related infrastructures.

5.1. Requirements analysis

The resulting conceptual model reflects the requirements taken from five semi-conductor companies. Our approach allowed us to get comparable view on the companies from different areas, as well as company specific requirements. The examined companies seem not to use the full theoretical potential of a modern MES. The average implementation score over all MES functions is 1.3 out of 4 points (cf. Table 1). We can explain this by our experience that e.g. a function is often not available or sufficiently implemented in the company's MES. In these cases, different software tools are used without an appropriate MES integration or automated interfaces. This missing integration is creating waste and decreasing efficiency. On the other hand, all of the involved companies show a high interest in improving the current implementation status (+1.1 points in average per MES function). Additionally, for seven of the ten MES functions, at least one company aims for a target implementation beyond the state-of-the-art.

5.2. SPCS conceptual model

We have designed the SPCS conceptual model in a general way, so that it is not only limited to applications within the semi-conductor industry, but also transferable to a wide range of industries. The model follows the propagated idea of the Internet of Things (IoT) to create a virtual image of the physical world [17]. The increased transparency and traceability allows improving the manufacturing process in detail or as a whole and enhances the overall agility and productivity across the supply chain [18]. A pre-requisite is the availability and quality of data, which is captured and processed autonomously [19]. In addition, the SPCS should fulfill "smart" characteristics, which is reflected by i) self-management through use of machine learning algorithms within the advanced DSS and ii) adaptability by analyzing the quality of decisions and improving its algorithms. Moreover, we recommend implementing a SPCS using a modular approach on a decentralized IT architecture. It can be seen as a framework or platform, thus, it is more adaptive to changes in the manufacturing setup and can be extended with less effort over time.

5.3. Integration and decentralization

Traditional MES have a centralized IT architecture. They are often monolithic and do not use open standardized interfaces [20]. High efforts in development, integration and maintenance make them expensive and highly inflexible. So, a full vertical and horizontal integration is usually not realized. Even though a centralized MES is quite powerful when is employed, it can hardly adapt and respond to a volatile and fast moving market on time [20].

However, there are ways to deal with the aforementioned challenges. The MES/SPCS of the future is built to support the paradigm shift of the fourth industrial revolution. In his letter from industry [21], Francisco Almada-Lobo describes a decentralized system, allowing autonomous decisions in a market-like manufacturing environment. It contains negotiating service providers and service consumers. It is vertically and horizontally integrated, and aligns with manufacturing business processes and the overall supply chain.

A cloud-based platform [22, 23] such as Virtual Fort Knox (VFK) already incorporates these thoughts. The developers promise an efficient and secure access to modular and flexible software solutions, which are independent of manufacturers. VFK provides an open marketplace environment for IT-services and applications, so that companies can digitalize their processes fast with low implementation efforts.

6. Outlook and future research agenda

Our next step is to apply single aspects of the SPCS conceptual model in the context of the SemI40 project. Thus, company-specific use cases have been defined, which are particularly focused on:

- The prediction of cycle times considering changing production parameters (R1)
- The development of a decision support system (R4, F4)

In the long-term, we will work on elaborating the SPCS features, adding additional ones, and investigating possibilities of an easy and cost-efficient integration in existing manufacturing environments.

Acknowledgements

A part of the work has been performed in the project Power Semiconductor and Electronics Manufacturing 4.0 (SemI40) under the grant agreement No 692466. The project is co-funded by grants from Austria, Germany, Italy, France, Portugal, and Electronic Component Systems for European Leadership Joint Undertaking (ECSEL JU) [5].

We also would like to thank our partners within the SemI40 project for their support, especially Ricardo Ferreira and our colleague Dr.-Ing. Fazel Ansari at the Vienna University of Technology.

References

[1] Sprock T, McGinnis LF. A Conceptual Model for Operational Control in Smart Manufacturing Systems. 15th IFAC Symposium on Information Control Problems in Manufacturing 2015; 48 (3): 1865-1869.
[2] Rajesri G, Krisna P. A methodology for Manufacturing Execution Systems (MES) implementation. Materials Science and Engineering 2016; 114: 1-10.
[3] Peneder M, Bock-Schappelwein J, Firgo M, Fritz O, Streicher G. Österreich im Wandel der Digitalisierung (Digitalization in Austria). Wien: WIFO; 2016.
[4] Monostori L. Cyber-physical Production Systems: Roots, Expectations and R&D Challenges. Variety Management in Manufacturing 2014; 17: 9-13.
[5] SemI40. http://www.semi40.eu/. Accessed 27 Apr 2017.
[6] Verein Deutscher Ingenieure (Association of German Engineers). VDI 5600 Blatt 1. Berlin: Beuth Verlag GmbH; 2015.
[7] Arnaut BM, Ferrari DB, de Oliveira e Souza ML. A requirements engineering and management process in concept phase of complex systems. IEEE International Symposium on Systems Engineering (ISSE) 2016.
[8] Sunk AW. Dissertation: Ein Vorgehensmodell zur IT-gestützten Parametrisierung des nächsten Zielzustands eines Wertstroms am Beispiel eines dezentral organisierten Unternehmensverbunds (A methodology for a IT-based parametrization of the next current state map of a value stream using the example of a decentrally organized corporate network). Wien: TU Wien; 2016.
[9] Meudt T, Rößler MP, Böllhoff J, Metternich J. Wertstromanalyse 4.0: Ganzheitliche Betrachtung von Wertstrom und Informationslogistik in der Produktion (Value stream mapping 4.0: A holistic approach on value stream and information logistics in producation). ZWF 2016; 111 (6): 319-323.
[10] Haefner B, Kraemer A, Stauss T, Lanza G. Quality Value Stream Mapping. Variety Management in Manufacturing 2014; 17: 254-259.
[11] Felsberger A, Oberegger B, Reiner G. A review of Decision Support Systems for Manufacturing Systems. I-KNOW 2016.
[12] Lingitz L, Morawetz C, Gigloo DT, Minner S, Sihn W. Modelling of Flexibility Costs in a Decision Support System for Mid-term Capacity Planning. Forty Sixth CIRP Conference on Manufacturing Systems 2013; 7: 539-544.
[13] Morawetz C, Sihn W. Model of a Decision Support System for a Least-Cost and Harmonized Capacity Adjustment in the Short- and Medium-Term Planning Horizon. 45th CIRP Conference on Manufacturing Systems 2012; 3: 20-25.
[14] Ansari F, Sassenberg C, Fathi M, Montino R. Integration of Knowledge Discovery Techniques in the Quality Management Model to Achieve Higher Target Quality. 14th IEEE International Conference on Emerging Technologies and Factory Automation (IEEE ETFA) 2009: 1-6.
[15] Can B, Heavey C. A demonstration of machine learning for explicit functions for cycle time prediction using MES data. WSC'16 Proceedings of the 2016 Winter Simulation Conference 2016.
[16] Brettel M, Bendig D, Keller M, Friederichsen N, Rosenberg M. Effectuation in manufacturing: how entrepreneurial decision-making techniques can be used to deal with uncertainty in manufacturing. CIRP 2014; 17: 611-616.
[17] Müller R, Hörauf L, Vette M, Speicher C. Planning and developing cyber-physical assembly systems by connecting virtual and real worlds. CIRP 2016; 52: 35-40.
[18] Yu Z, Yan H, Edwin Cheng TC. Benefits of information sharing with supply chain partnerships. Industrial Management & Data Systems 2001; 101 (3): 114-121.
[19] Caggiano A, Segreto T, Teti R. Cloud Manufacturing Framework for Smart Monitoring of Machining. 5th CIRP Global Web Conference – Research and Innovation for Future Production (CIRPe) 2016; 55: 248-253.
[20] Bauer D. Movement towards service-orientation and app-orientation in manufacturing IT. CIRP ICME 2016.
[21] Almada-Lobo F. The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES). Journal of Innovation Management 2015; 3 (4): 16-21.
[22] Stock D, Stöhr M, Rauschecker U, Bauernhansl T. Cloud-based Platform to facilitate Access to Manufacturing IT. CIRP 2014; 25: 320-328.
[23] Fraunhofer-Institut für Produktionstechnik und Automatisierung (IPA). Virtual Fort Knox. https://www.virtualfortknox.de/en/. Accessed 27 Apr 2017.