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Operational planning and control in eto-companies : thoughts on improving of existing performance measurement practices in the industry 4.0 context

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OPERATIONAL PLANNING AND CONTROL IN ETO-COMPANIES:

THOUGHTS ON IMPROVING OF EXISTING PERFORMANCE MEASUREMENT PRACTICES IN THE INDUSTRY 4.0 CONTEXT

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THIS INTRODUCTORY WORKING PAPER IS A PART OF THE AUTHOR'S PhD STUDY PROGRAMME AT MOLDE UNIVERSITY COLLEGE – SPECIALIZED UNIVERSITY IN LOGISTICS

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CONTENTS

SUMMARY

This working paper focuses on emerging strategic requirements for next generation, digitalized supply chain management in the Industry 4.0 context. These requirements are then converted to the operational level and linked particularly to the process of operational supply chain planning. The research question is how operational planning can be controlled and improved while keeping the linkages to companies' digital strategies intact.

Key-words: Industry 4.0, supply chains, engineer-to-order, operational planning, control, key performance indicators, review, case study, framework

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INTRODUCTION

Digitalization of manufacturing supply chains and operations is constantly gaining attention both, from researchers and practitioners worldwide. Concepts like the Internet of Things, Cyber-Physical Systems, Big Data and Cloud Manufacturing are often considered under the heading of Industry 4.0. Both, researchers and practitioners believe that future of industrial manufacturing is autonomy, visibility and interoperability. Increased supply chain responsiveness, flexibility, collaboration and, ultimately, profitability are some of the benefits that can be achieved by utilizing possibilities of ubiquitous connectivity and real-time analytics (Wamba and Barjis, 2013; Wortmann and Fluchter, 2015; Xu, 2012).

However, significant challenges need to be solved not only from a technological point of view, but also from a business perspective, where the introduction of connected products, autonomous resources and automated operations raise a number of important issues related to supply chain management, and planning in particular. Utilization and management of significantly increased amount of data, changing roles of supply chain partners and reevaluation of performance metrics are relevant examples (Bharadwaj, El Sawy, Pavlou and Venkatraman, 2013; Davis, Edgar, Porter, Bernaden and Sarli, 2012; Porter and Heppelmann, 2014; Wortmann and Fluchter, 2015).

This paper focuses on emerging strategic requirements for next generation, digitalized supply chain management in the Industry 4.0 context. These requirements are then converted to the operational level and linked particularly to the process of operational supply chain planning. The research question is how operational planning can be controlled and improved while keeping the linkages to companies' digital strategies intact.

As an empirical research on operational planning performance is limited, especially in the Industry 4.0 context (Gunasekaran, Patel and McGaughey, 2004; Ivanov and Sokolov, 2013; Mandal, 2012), the author would like to trigger a discussion and propose a framework for next generation, improved planning and control. Furthermore, as the literature review reveals, there is still lack of research focusing on robust conceptualization and operationalization of the Industry 4.0 phenomenon, giving companies a practical and well-defined roadmap for implementation (Erol, Schumacher and Sihn, 2016). Hence, this paper can be considered as an initial attempt to both, systematize and operationalize emerging Industry 4.0 requirements for future supply chains. The study is therefore not exhaustive, and the focus is on operational planning and control domain in order to establish boundary conditions and deliver acceptable depth of analysis. The framework proposes 12 new or re-defined key performance indicators that can capture and handle features of technology-enabled supply chain management. Furthermore, the framework is built upon the analysis of current research as well as the results of the case study that was carried out in a Norwegian ETO-company.

METHOD

The paper is organized as follows: A brief review of recent developments towards the Industry 4.0 concept, including last advancements in enabling ICTs and a systematic approach to emerging requirements for supply chain management; A description of the planning process in the ETO-supply chain; A discussion regarding performance measurement of operational planning in supply chain context; A framework for operational performance measurement as a response to emerging requirements for next generation planning and control in ETO-supply chains. The empirical data are provided by the case study in order to support the initial theoretical considerations. The data are collected from the case company's ERP-system directly as well as indirectly, tested SQL-queries and qualitative interviews with people from the Planning Department and ICT/ERP Department.

INDUSTRY 4.0 AND DIGITALIZATION OF SUPPLY CHAINS

The concept of Industry 4.0.

The fields of application for Internet-based information and communication technologies are as numerous as they are diverse, as new solutions are increasingly extending to virtually all areas of everyday. One of the most prominent areas of increasing application is the manufacturing industry. The development of intelligent production systems and connected production sites is often facilitated by technologies of the Internet of Things, Cyber-Physical Systems, Big Data and Cloud Manufacturing (Lee, Bagheri and Kao, 2015; Monostori, 2014; Soldatos, Gusmeroli, Malo and Di Orio, 2016; Schuh, Potente, Wesch-Potente, Weber and Prote, 2014; Wortman and Fluchter, 2015).

These concepts address the vision of future digitally enabled production and are commonly subsumed by the visionary concept of a Fourth Industrial Revolution or Industry 4.0. The vision of Industry 4.0 propagates a fundamental paradigm shift in production industries, which is characterized by a new level of socio-technical interaction (Erol, Schumacher and Sihn, 2016). The internet and supporting technologies (e.g. embedded systems) serve as a backbone to integrate human and machine agents, materials, products, production lines and processes within and beyond organizational boundaries to form a new kind of intelligent, connected and agile value chain (Erol, Jäger, Hold, Ott and Sihn, 2016; Rüßmann et al., 2015).

Central aspects of the Industry 4.0 can be further specified through three paradigms: the Smart Product, the Smart Machine and the Augmented Operator (Weyer, Schmitt, Ohmer and Gorecky, 2015). The smart factories are embedded in the intercompany value network, which is encompassed by end-to-end engineering, resulting in seamless convergence of the digital and physical world. The results are smart products that are uniquely identifiable and locatable at all times during the manufacturing process. Smart products are customizable and the incorporation of individual customer- and product specific features into the design and configuration is enabled - at the costs of mass products (Wang et al., 2016). On an employee level, the Industry 4.0 vision propagates, that workers are able to control, regulate and configure smart manufacturing resource networks and manufacturing steps in real-time. Routine tasks are taken over by smart, autonomated machines, so that employees can focus on creative, value-adding activities, such as improvement and optimization (Erol, Schumacher and Sihn, 2016).

Furthermore, as volatile markets and global, inter-industrial networks are creating a radically more dynamic and complex market environment, companies have to respond with considerably greater on-demand flexibility and enhanced resource deployment. Industry 4.0 addresses this issue by making it possible to gather and analyze data across machines and people. This, in turn, enables faster and more efficient manufacturing with dynamic re-engineering processes and delivers the ability to respond flexibly to disruptions and failures (Bauer, Hämmerle, Schlund and Vocke, 2015; Erol, Schumacher and Sihn, 2016; Rüßmann et al., 2015; Weyer, Schmitt, Ohmer and Gorecky, 2015).

For the abovementioned purposes, the supply chains of Industry 4.0 will become highly transparent and integrated. The physical flows will be continuously planned, controlled and managed on digital platforms. Ultimately, Industry 4.0 advocates that the shop-floor will become a marketplace of capacity and capability (supply) represented by the production system and production needs (demand) represented by the value creation networks. Hence, the manufacturing environment will to a certain extent organize itself based on a multi-agent like system. This decentralized system with competing targets and contradicting constraints will generate a holistically optimized system, ensuring only efficient operations will be conducted (Almada-Lobo, 2015; Soldatos et al., 2016).

Enabling technologies

Having outlined the main features and fundamental philosophy of Industry 4.0, the paper continues by presenting recent advancements in enabling information and communication technologies for the next generation supply chain management.

Extensive approaches of a technology-push in the Industry 4.0 context are identified, generalized and presented in the **Figure 1** below (Lasi et al., 2014).

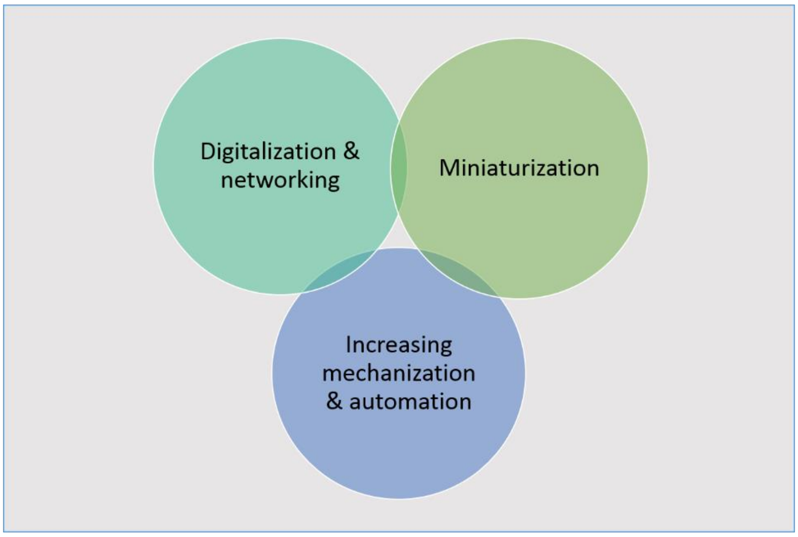

Figure 1. Main trends regarding technology-push in Industry 4.0 context (Lasi et al., 2014).

Further increasing mechanization and automation: In the manufacturing process, more and more technical aids, such as robots, will be used in order to support physical work. Furthermore, automatic solutions will adopt the execution of versatile operations, which consist of operational, dispositive and analytical components such as "autonomous" manufacturing cells which independently control and optimize manufacturing in various steps (Lasi et al., 2014). Data collected will be processed automatically with advanced analysis, transformed into predictive algorithms, and applied to automated systems in order to increase productivity, improve efficiency and reduce marginal costs of production (Russo et al., 2015).

Digitalization and networking: The core concept is that everyday objects can be equipped with identifying, sensing, networking and processing capabilities that will allow them to communicate with one another and with other devices and services over the Internet (Atzori, Iera and Morabito, 2010; Russo et al., 2015; Whitmore, Agarwal and Da Xu, 2015). Intelligent infrastructure will be designed to be open, distributed and collaborative. The increasing digitalization of all manufacturing and manufacturing-supporting tools is resulting in the registration of an increasing amount of actor- and sensor-data which can support functions of control and analysis. Digital processes evolve as a result of the likewise increased networking of technical components and, in conjunction with the increase of the digitalization of produced goods and services, they lead to completely digitalized environments. Those are in turn driving forces for new technologies such as simulation, digital protection or augmented reality (Lasi et al., 2014).

Miniaturization: Simultaneously there is a trend towards miniaturization. While computers required significant space some years ago, nowadays devices with a comparable or even considerably better performance can be installed on few cubic centimeters. In this regard, technologies like Radio Frequency Identification (RFID), short-range wireless communications, Real Time Location Systems (RTLS), and sensor networks ubiquity enable new fields of application, especially in the context of production and logistics (Wamba and Barjis, 2013; Lasi et al., 2014). Not only do these microchips help to keep track of other objects, but many of these devices sense their surroundings and provide information about them to other machines and to human beings for planning and control purposes (Russo et al., 2015).

Emerging strategic requirements for supply chains in Industry 4.0 context

As mentioned in the sections above, the development of technologies and ongoing conceptualization of Industry 4.0 are considered as a competitive response to fast-changing markets and customer needs in globalized manufacturing industry (Soldatos et al., 2016). This in turn can be aggregated into a set of requirements for the next generation supply chains in order to stay competitive. A brief review of Industry 4.0-related literature is used to aggregate these emerging supply chain requirements that can be addressed by use of the newest information and communication technologies and new models of management. The requirements, presented in **Figure 2** will then be linked to the function of supply chain planning and, ultimately, associated with proposed key-performance indicators for controlling and improving the operational planning process itself.

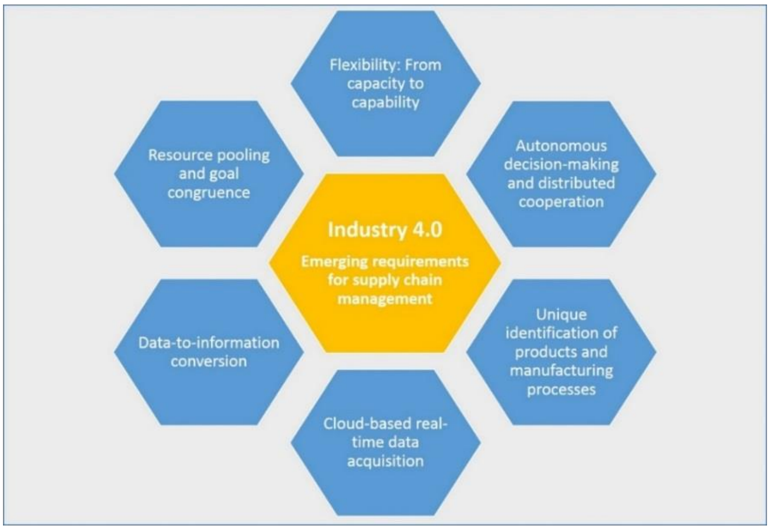

Figure 2. Emerging requirements for supply chain management in the Industry 4.0 context.

From capacity to capability: Flexibility

The volatility of sales markets is reflected in increasingly heavy fluctuations in orders, shorter order delivery times and a diminished ability to plan ahead. To remain competitive in the traditional senses of short delivery times, high productivity (or lowest possible costs) and optimum quality despite this shift in the underlying conditions, manufacturing companies are required to increase the flexibility of their machines and equipment, their material procurement (and their supply chain) and their personnel deployment strategies (Bauer et al., 2015).

The smart factory is an important feature of Industry 4.0 that addresses integrated and networked manufacturing systems for smart production. These combine the smart objects with big data analytics. The smart objects can be dynamically reconfigured to achieve high flexibility whereas the big data analytics can provide global feedback and coordination to achieve high efficiency. Future internet technologies are also gradually deployed on the shopfloor, as means of transforming conventional centralized automation models (e.g., SCADA (Supervisory Control and Data Acquisition), MES (Manufacturing Execution Systems), ERP (Enterprise Resource Planning)) on powerful central servers) towards more decentralized models that provide flexibility in the deployment of advanced manufacturing technology as well as production of customized and small-lot products efficiently and profitably (Soldatos et al., 2016; Wang et al., 2016).

The abovementioned issues witness a remarkable shift from capacity to capability which aims at increasing manufacturing flexibility towards responding to variable market demand and achieving high-levels of fulfillment of customer requirements (Soldatos et al., 2016).

Autonomous decision-making and distributed cooperation

Situation-dependent control of global and local production and logistics processes is of increasing relevance. Decentralized and autonomous approaches are considered to be especially promising in this context. These approaches have inherent rapid reactivity towards disturbances, which depends on current data from the production process. The particular potential of decentralised and autonomous approaches in job shop manufacturing originates from the enormous number of decision alternatives which complicate scheduling and rescheduling of job shops. For example, rescheduling, i.e., updating the schedule in case of disturbances, has been in need of better algorithmic solutions for decades and remains a focus of research. The higher the complexity and dynamics (e.g., the frequency of disturbances) of a production system, the sooner the (re-)scheduling algorithms are pushed to their limits, especially as the basic assumptions in scheduling research are often far from the complexity of real production systems. In contrast, autonomous control approaches focus on the use of existing flexibility potentials in the production logistics system. For example, decision-making for machine scheduling is performed in a decentralized manner in heterarchical structures, rather than via central scheduling. The resources know their capabilities and their state. They are able to decide between a set of alternative actions, orchestrate and execute necessary actions without or with minimal human control (Grundstein, Freitag and Scholz-Reiter, 2017; Rosen et al., 2015).

Another important requirement for supply chain management in the Industry 4.0 context is the "collaborative automation". The aim is the development and implementation of tools and methods to achieve flexible, reconfigurable, scalable, interoperable network-enabled collaboration between decentralized and distributed embedded devices and systems. This trend has been accompanied by a technological evolution characterized by the penetration of computational capabilities, i.e., data and information processing, into the mechatronics, transforming gradually the traditional shop floor into an ecosystem, where networked systems are composed by smart embedded devices and systems, as well as by customers and business partners in business and value processes, interacting with both physical and organizational environment, pursuing well-defined system goals (Leitão, Colombo and Karnouskos, 2016; Ramanathan and Gunasekaran, 2014).

Unique identification of products and processes

The aim of visibility requirement is to foster planning, control and agility of operations associated with the product and to improve customer experience of the product. In recent times there has been an upsurge of academic and commercial interest in product visibility (Musa, Gunasekaran and Yusuf, 2014). This issue becomes an important competitive requirement as well (Babiceanu and Seker, 2016).

As mentioned before, virtual manufacturing applications enable connected supply chains, informed manufacturing plants comprising informed people, informed products, informed processes, and informed infrastructures, thus enabling the streamlining of manufacturing processes (Soldatos et al., 2016). Furthermore, while the use of IC technologies in supply chains is not new, the pervasiveness and ubiquity enable the use of these technologies across organizational and geographic boundaries, mitigating the bullwhip effect, reducing counterfeiting and improving product traceability (Whitmore, Agarwal and Xu, 2015).

The concept of “intelligent product” has a key role in the next generation manufacturing systems (Putnik et al., 2015). IT is becoming an integral part of the product itself. Embedded sensors, processors, software, and connectivity in products, coupled with a product cloud in which product data is stored and analyzed and some applications are run, are driving dramatic improvements in product functionality and performance (Porter and Heppelmann, 2014). This means that in a supply chain context, a product is not just a physical resource but a key element in the information infrastructure, interacting with other products, processes and stakeholders. The automatic monitoring and context awareness enable a better performance of information systems such as Supply Chain Management, Enterprise Resource Planning or Warehouse Management Systems (Putnik et al., 2015).

Ultimately, connectivity serves a dual purpose. First, it allows information to be exchanged between the product and its operating environment, its makers, its users, and other products and systems. Second, connectivity enables some functions of the product to exist outside the physical device, in what is known as the product cloud. Intelligence and connectivity enable an entirely new set of product functions and capabilities, which can be grouped into four areas: monitoring, control, optimization and autonomy (Porter and Heppelmann, 2014).

Real-time data acquisition in supply chains

Effective and efficient production requires real-time control and decision making. Decision processes have to consider overall system goals and optimization. This requires processing of comprehensive models and accessing network data, in real-time (Gölzer, Cato and Amberg, 2015). Data that are correct when assessed, but updated very infrequently, may still hamper efforts at effective managerial decision making (Hazen, Boone, Ezell and Jones-Farmer, 2014). Hence, real-time information about the location, quantities and states of goods in the supply chain provides managers with tools to make adjustments to delivery schedules, place replenishment orders, place emergency orders, change transportation modes, and so forth (Souza, 2014). New and improved architectures in the Industry 4.0 context integrate and process a large amount of production data collected from distributed plants and meet actionable decision-making requirements in a very short time (Guo, Ngai, Yang and Liang, 2015).

Furthermore, sharing real time information between supply chain nodes at both local and global levels is essential for greater supply chain responsiveness (Reaidy, Gunasekaran and Spalanzani, 2015). With the aid of sensors cyber-physical systems are able to directly collect, process and evaluate data, while actuators allow them to react to changes and digital communication facilities allow them to interact with other cyber-physical systems. Hence, it is required that both, the physical and the digital worlds are connected where data is independently and mutually exchanged in real time, thus allowing a mutual control system (Seitz and Nhuis, 2015).

Data-to-information conversion

The requirement of "Data-to-information" conversion means that meaningful information has to be inferred from an enormous amount of data acquired throughout the supply chain or manufacturing network (Lee, Bagheri and An-Kao, 2015). For example, the massive amount of raw data available from a factory floor creates opportunities to add intelligence to the manufacturing process. However, the volume, velocity, and variety of the generated data have provided industries with a noticeable challenge: how to extract actionable information from this big data? (Lee, Bagheri and Jin, 2016).

Unstructured data makes up to 95% of the data labeled as "Big Data". Literature characterizes Big Data as large data sets having at least three distinct agreed dimensions. Called the Big Data three "V's", these three main dimensions are agreed across the literature as follows: Volume: data is generated in large amounts. Variety: data is generated in different formats. Velocity: data is generated almost continuously. Appropriate and efficient analytical methods are needed to process the large amounts of unstructured heterogeneous data collected continuously in formats such as text, audio, video, log file, or others. (Babiceanu and Seker, 2016; Lee, Bagheri and Jin, 2016). Ultimately, right translation of raw data into actionable information brings out enormous business values as well (Lee, Bagheri and Jin, 2016).

Resource pooling and goal congruence

The last requirement for supply chain management considered in this paper is resource-pooling and goal congruence. These are the two interrelated collaborative practices that are central to coordination (Schuh et al., 2014; Wu, Greer, Rosen and Schaefer, 2013). The explanation is as follows: decision proposals for the planner made by the cyber-physical support system should be made in consideration of the entire production system. This prevents that a change in the schedule in one section of the manufacturing process causes a massive loss in logistical performance in other sections (Schuh et al., 2017). The negative effect is often related to decisions that are based on local information. Thus, the load may not be balanced, efficiency may not be the highest, or deadlocks may occur. One of the big data analytics blocks (the coordinator or planner) can solve this issue by resource pooling (Wang, Wan, Zhang, Li and Zhang, 2016).

Resource-pooling encompasses aggregation of necessary information, equipment and human resources to certain tasks in order to reach the collaborative goal at different supply chain levels. One difficulty of resource-pooling is that the collaborative entities often compete for limited resources elsewhere in the manufacturing network. For resolving the competition for resources, goal-congruence is crucial (Pathak, Wu and Johnston, 2014; Schuh et al., 2014; Wang, Wan, Zhang, Li and Zhang, 2016).

Goal congruence describes the mutual understanding and agreement on the overall goal by the collaborating entities. With a high degree of goal-congruence, productivity can be increased, since the objectives and activities of the decision makers are aligned and do not conflict with each other (Schuh et al., 2014). The basic hypothesis is that this integrated method achieves a higher logistic performance than combinations of methods, which fulfil single manufacturing task control isolated from each other (Grundstein, Freitag and Scholz-Reiter, 2017). Such decentralized system with competing targets and contradicting constraints becomes a holistically optimized system, ensuring only efficient operations will be conducted (Almada-Lobo, 2015).

PLANNING PROCESS IN AN ETO-SUPPLY CHAIN

After aggregating and presenting some of the emerging requirements for supply chain management in the Industry 4.0 context, the paper continues and approaches the case study. For that matter it is necessary to provide a brief introduction to ETO-manufacturing peculiarities and challenges with regard to planning and control issues as they are seen today.

ETO-manufacturing

The ETO supply chain has emerged as a major supply chain structure and is set to become of increasing importance as more customized products are demanded across a range of industries. ETO manufacturing not only takes advantage of common manufacturing requirements and efficiency, but also allows for customization into unique combinations. Unique orders are handled as a project. For ETO manufacturing, every product is the ultimate result of a project. Thus, the methods used for production planning and control of mass production are not suitable in this environment (Gosling and Naim, 2009; Yang, 2012).

ETO supply chains involve multiple companies performing diverse activities during a project, such as: design, engineering, procurement, manufacturing, assembling and commissioning. Some typical but not exhaustive examples of ETO manufacturing are: shipbuilding, heavy equipment and construction. In general, ETO supply chains produce low volumes of a high variety of products and allow customers to demand products which are developed in order to exactly satisfy their needs. The challenge is that ETO supply chains have to cope with diverse customer requirements and deliver the highest quality of product in a highly uncertain environment. Furthermore, coordination is a relevant aspect of the decision-making process that maintains the order and stability of a system. To be fully coordinated, a supply chain requires that all decisions are aligned to accomplish a global system objective. When interdependent activities are performed by different partners, coordination is even more challenging, because of the lack of common knowledge and increased supply chain complexity (Gosling and Naim, 2009; Mello, Strandhagen and Alfnes, 2014). The complexity issues are presented below.

Complexity issues

Supply chain complexity can make planning and control of supply chains more challenging, and can introduce risks and vulnerability. Several research contributions state that complexity has a negative effect on delivery performance (Blome, Schoenherr and Eckstein, 2014).

Considering the ETO environment, manufacturing involves physical stages (e.g., component manufacturing, assembly and installation) and non-physical stages (e.g., tendering, engineering, design and process planning). This is associated with chaotic production in high-complexity and high-uncertainty situations, in which the ability to address demand instability and to respond to demand modifications over time is crucial (Carvalho, Oliveira and Scavarda, 2015).

Furthermore, there are two widespread types of complexity considered by supply chain and operations researchers. The first one is the structural complexity (also static or detail complexity) which refers to the number and variety of elements defining the system. The second one is the dynamic complexit*y* (or operational complexity) and refers to the interactions between the elements of the system. In practice, these aspects are often closely interrelated, because the larger the number of varied elements, the greater is the possible number of interactions and thus the variety of behaviors and states the system may exhibit. This is especially true for the ETO supply chains (Blome, Schoenherr and Eckstein, 2014; Bode and Wagner, 2015).

Ultimately, in order to maintain a competitive advantage, the mentioned complexity issues have to be alleviated by robust and adapted planning and control methods in interrelated ETO supply chains. The next chapter provides a brief overview on research contributions regarding the matter.

Planning and control process as a tool against supply chain complexity and vulnerability

The four core supply chain processes are Plan, Source, Make and Deliver. Plan defines the planning and control activities involved in running the other three collaborative supply chain processes and is executed on strategic, tactical and operational levels. It contains sub-processes dealing with resource planning, demand planning, capacity planning, production planning, inventory planning, and distribution planning (Angerhofer and Angelides, 2006; Pero, Rossi, Noe and Sianesi, 2010; Subramanian, Rawlings, Maravelias, Cerillo and Megan, 2013).

Supply chains consist of different structures: business processes and technological, organizational, technical, topological, informational, and financial structures. All of these structures are interrelated and change in their dynamics. Especially in adaptive supply chains with high complexity and dynamics such as ETO, the issue of how to achieve structural comprehensiveness, responsiveness, and flexibility as well as to avoid structural incoherency and non-consistency by supply chain planning and operations is very important. The adaptation of one structure causes changes in the other related structures. To ensure a high responsiveness level, the supply chain plans must be formed extremely quickly, but must also be robust. That is why it becomes very important to plan and run supply chain plans in relation to all the structures (Carvalho, Oliveira and Scavarda, 2015; Gosling and Naim, 2009; Ivanov, Sokolov and Kaeschel, 2010).

Furthermore, a large part of the production industry has been confronted with continually increasing competition for many years. While the pressure to reduce costs steadily grows, their logistic performance is simultaneously gaining importance. This influential development has meant that it is no longer sufficient to exclusively focus on product features in order to maintain market success. Whereas, products barely differ in prices and quality and thus offer little room for an enterprise to distinguish themselves, realizing a strong logistic performance creates the possibility for a company to optimally position themselves against competing producers. In addition to realizing a strong logistic performance, characterized by quick delivery times and high delivery reliability, today's production logistics also focus on diminishing costs by maintaining a minimum of stock and highly utilizing capacities. Demands on the logistic performance and costs in complex manufacturing environments will continue to grow in the future. It will thus become more important to focus on production planning and control (Blome, Schoenherr and Eckstein, 2014; Seitz and Nyhuis, 2015).

Hence, production planning, scheduling and control aspects become more and more difficult to overlook by manufacturing managers or operators. This growing complexity in manufacturing in strongly interdependent networks leads to the desire for intelligent support capabilities (Weyrich et al., 2017). Production planning and control have to take more factors into account than before and orchestrate a great amount of technical, mechanical and digital processes with minimal tolerance of process time. Therefore, the production management needs to achieve a new level of automatization and autonomization (Oks, Fritzsche and Möslein, 2017).

However, as these changes are already taking place, the process of planning and control to a certain extent is still managed by humans, including optimization and improvements. While the planning algorithms stay the same, new enabling tools and performance indicators become available. The paper continues by presenting the situation regarding performance measurement of planning and control processes as well as importance of actually doing this.

MEASURING PERFORMANCE OF OPERATIONAL PLANNING

Research contributions considering planning performance

Although the domain of supply chain performance synthesis and analysis in terms of real-time dynamics and uncertainty becomes more and more important in practice, it has received little systematic consideration so far in the literature. Along with the great advantages of recently developed supply chain optimization approaches, the models as currently implemented in APS (Advanced Planning and Scheduling) and SCM (Supply Chain Management) information systems still do not consider important practical operability objectives such as robustness, stability, and flexibility. Furthermore, there is a lack of empirical analysis and case studies on performance metrics and measurements in a supply chain environment. This situation creates a gap between theory and practice and can be regarded as an opportunity for research and development, which could significantly improve the practice of SCM (Estampe, Lamouri, Paris and Djelloul, 2013; Gunasekaran, Patel, Ronald and McGaughey, 2004; Ivanov and Sokolov, 2013).

Furthermore, it has been shown that research in performance measurement mechanisms for an extended enterprises such that of an ETO-environments is one area that is lagging behind that of traditional performance measurement systems (Addo-Tenkorang, Kantola, Helo and Shamsuzzoha, 2016).

Different authors have strived to identify the shortcomings of certain performance measurement systems: relatively few links to strategy, measurements largely geared toward cost instead of non-cost indicators, imbalanced approach, lack of customer or competitor orientation, absence of inter-organisational vision, and an absence of a systemic approach (Estampe, Lamouri, Paris and Djelloul, 2013).

Moreover, supply chain performance is affected by exogenous variables (e.g. demand and lead time variability), supply chain management and planning decisions and supply chain design decisions (Pero, Rossi, Noe and Sianesi, 2010). In practice, once the supply chain performance measures are developed adequately, managers have to identify the critical key performance indicators (KPIs) that need to be improved. However, it is difficult to figure out the intricate relationships among different KPIs and the order of priorities for accomplishment of individual KPIs. As a matter of fact, determination of priorities within a given set of KPIs has become a bottleneck for many companies in their endeavors for improving their supply chain management. As these problems have received relatively less attention in previous research, significant gaps remain between practical needs and their effective solutions (Cai, Liu, Xiao and Liu, 2009). The production planner often has no appropriate evaluation variables for control decisions. With several production planners on duty, several locally optimal decisions can exist, which can have a negative effect on global corporate targets (Schuh et al., 2017).

It is therefore important for a firm to adopt information systems that are aligned to its supply chain, that is, adopt information systems that facilitate the particular processes of its supply chain and provide information about parameters that assess specific goals of its particular supply chain strategy (Qrunfleh and Tarafdar, 2014).

Key-performance indicators

Supply chain management and planning decisions concern the definition of the policies to manage material and information flows across the entire network both at strategic, operational and tactical levels (Pero, Rossi, Noe and Sianesi, 2010).

There exist different steps of a complex performance management system for e.g. identifying measures, defining targets, planning, communication, monitoring, reporting and feedback. These processes have been embedded in most information system solutions, such as i2, SAP, Infor M3, Oracle EPM, etc. These system solutions measure and monitor key performance indicators (KPIs) which are crucial for optimizing supply chain performance. A performance measure is a set of metrics used to quantify the efficiency and/or effectiveness of an action. The term ‘‘metric’’ refers to definition of the measure, how it will be calculated, who will be carrying out the calculation, and from where the data will be obtained. The main challenge is to identify the key performance measures for value-adding areas of a supply chain (Mandal, 2012).

In manufacturing, performance indicators such as on-time delivery (OTD), quality, availability, efficiency, instate overall equipment efficiency (OEE) or downtime are well established in industrial production. There is a large number of standards and guidelines defining performance indicators and their functions for production (Tracht, Niestegge and Schuh, 2013).

However, there exist several discrepancies in performance measurement systems that are also found in the wider performance management literature. They include: a) Lack of connection with strategy; b) Focus on cost to the detriment of non-cost indicators; c) Lack of a balanced approach; d) Insufficient focus on customers and competitors; e) Loss of supply chain context, thus encouraging local optimization, and f) Lack of system thinking (Mandal, 2012).

Furthermore, in the Industry 4.0 context, a cyber-physical production system is characterized into two levels: the physical and the cyber level. The physical indicators describe the characteristics of physical objects, e.g. hardware of automation systems which is well covered by performance indicators. The "cyber" aspect might have an impact and enhance the performance. The quality of a production can certainly be measured efficiently with existing performance indicators independent of any technologies as the shop floor performance matters. However, there might be different performance indicators illustrating the ability to make the right decision at the right time or decide on the architecture of the manufacturing system (Weyrich et al., 2017).

Therefore, the case study presented below is an attempt to look at the measurement of planning and control performance through the lens of Industry 4.0, capturing changes in both, physical and cyber aspects mentioned above.

CASE STUDY: ADDRESSING THE EMERGING REQUIREMENTS FOR SUPPLY CHAINS BY FINE-TUNING PERFORMANCE MEASUREMENT OF THE PLANING AND CONTROL PROCESSES

The company

The case company is family-owned and located in Norway. The products are high-value, complex machinery for the maritime industry. The production model is Enginner-to-Order (ETO). The brand is global and well-recognized in the industry, and the company has established strong market positions in their key market segments. All manufacturing activities are carried out locally, while sales are global, with agencies in 24 countries. Furthermore, the owners and management of the company display a strong interest in digitalization of their manufacturing operations and supply chain, including planning and control activities. The digital strategy is well documented and communicated at all levels both internally and externally. However, the change towards digitalization is a complex process and implementation is happening gradually rather than a fast changeover. For example, the autonomy level in manufacturing resources or software is still relatively low, while automation is gaining speed. This is a common phenomenon in manufacturing industry in general, and there are various reasons that are affecting the pace. The next paragraph will present some of the challenges faced in the context of planning and control.

The challenges

The company and its operations are affected by both, structural and operational complexity (Blome, Schoenherr and Eckstein, 2014; Bode and Wagner, 2015).

The structural complexity encompasses issues such as factory layout (built during many years, external space limitations, production volume increase, different logistics requirements through time, some logistics flows are disrupted as a result), amount of internal resource groups (approximately 60, all have their own short term plans that must be coordinated), size of manufacturing network / value chain (approximately 500 local, national and global suppliers, approximately 50 national and global customers, several external actors, such as classification companies), and complexity of manufactured products (several thousand components and sub-components in a final product).

Furthermore, the operational complexity is present as well. There is approximately 6000 material transactions daily (registered in the ERP system) as well, as approximately 11 000 SKU's available at the central warehouse. Moreover, intense verbal communication throughout the supply chain is a significant part of information flow in addition to formal transactions in the ERP system. Another important issue is a relatively high amount of systems and software used for documentation, transaction and change registration and communication purposes, among other. Unique and standard identification of products and components in the entire supply chain is not implemented yet as well, giving room for potential misunderstandings, especially in frequent situations where change orders are planned and released into production. Ultimately, the dynamism of an ETO-production where drawings are made and changes occur while producing makes control and planning even more complex.

Given high complexity and high-cost production premises in Norway and the nature of the ETO production, the company needs highly flexible, dynamic and responsive operations' structures and controls in order to stay competitive in the global market. This makes efficient organization, planning and control of operations highly challenging (Bauer et al., 2015; Soldatos et al., 2016; Venkataraman, 2009; Wang et al., 2016).

It is obvious that a vision of digital manufacturing will lead to an increased technical and organizational complexity of manufacturing processes on the micro and macro level which imposes substantial challenges especially to small- and medium-sized manufacturing companies. Challenges are not limited to the financial investment required for the acquisition of new technology but are also related to the availability of qualified staff on all organizational levels that is able to cope with the increasing complexity of future production systems (Erol, Jäger, Hold, Ott and Sihn, 2016).

Current state of planning and control performance measurement

Currently, the company uses its ERP-system Infor M3 and external, integrated business intelligence applications for, among other, planning, coordination and control activities.

The author argues that the existing performance measurement system is relatively simple and general with low detail levels and low operational value. Connections to the company's digital strategy can be enhanced to a large degree as well.

A widespread performance indicator OTD or "on-time delivery" is used in many internal resource groups as well as procurement, together with popular quality-related indicators. The reports for analysis are generated by external business intelligence application that acquires data directly from company's ERP system. The data is communicated to all involved parts in a monthly meeting where possible improvements are discussed and planned.

The Planning Department carries the responsibility for planning, coordinating and control activities. The performance of this process is currently measured by using the **OTD** and "Action Required" (**AR**) indicators.

OTD indicates the percentage of amount of working orders that are accomplished on time (planned finish date in the ERP system) and the total amount of working orders in a given interval of time (1 month in this case).

The AR indicator is the amount of "action required" messages in the Material Plan (ERP) and is under frequent surveillance, depending on responsible planner's capacity / workload. An "action required" message appears automatically in the Material Plan in the ERP system when the system discovers that the specific working order is deviating from the planned start/finish date, due to dynamism in production, failures in transaction reporting and wrong information in supply chain (too early – overproduction, too late – delay, no demand – delete required). The planner has three choices when he/she sees the message: a) Re-plan the working order (change the dates so the order moves to a right queue place in the Material Plan; b) Force the working order to a desired place in the Material Plan by manually assigning the priority (ignores the dates) or c) Delete the order that has no matching demand and inappropriately uses the capacity of resources. If the plan is perfect (controlled and updated continuously) there should be no AR-messages in the ERP system, meaning that all working orders are carried out on time and according to the demand, as planned. However, given the mentioned network, complexity and dynamics issues in the ETO production this is hardly achievable. In addition the result is significantly dependent on responsible planner's workload and capacity issues that define how often the AR messages can be manually controlled and eliminated. The ERP system has an option for automated control and correction of "action required" messages. However, the company currently prefers manual corrections as some of the "action required" messages are made on purpose, while some of the system-made corrections can result in dramatic consequences if done inappropriately.

Another issue that applies to both indicators used is their operational value and linkages to company's digital strategy. A defined acceptable rate of OTD and a certain (low) amount of AR messages are current planning and control performance targets. However, these results are often accumulative values of many other sub-processes and activities. Therefore, the author argues that measuring and controlling the performance of these would increase operational value of performance measurement according to firm's digital strategy, enhance ownership of various processes, increase scope of measurement in the supply chain, focus on relevant root-cause analyses and take advantage of enabling technologies in the Industry 4.0 context.

The next chapter sums up the paper so long and provides a conceptual framework for planning and control in the case company that considers all the issues mentioned previously.

A framework for next generation planning and control

Given the emerging Industry 4.0 requirements for future supply chains, recent developments in enabling IC technologies and the challenging nature of manufacturing in the ETO-environments, the process of planning and control has to be re-evaluated, considering the issues mentioned. The emerging requirements presented in this paper are mostly general and apply to manufacturing operations and supply chains at a strategic level. However, as the unit of analysis in this paper is operational planning and control and their performance measurement, the strategic requirements are broken down to the operational level. The **Table 1** below is based on data collection at the case company and connects the described strategic supply chain requirements (**Figure 2**) with operational issues related to planning and control and, ultimately, presents proposed key performance indicators for further discussion. A broader description of proposed indicators with associated mathematical expressions follows in **Table 2**.

Table 1. Key performance indicators for operational planning and control in the Industry 4.0 context.

Emerging strategic requirements for operations and supply chains	Corresponding issues regarding planning / control at the operational level at the case firm. Qualitative interviews.	Corresponding KPIs for operational planning and control. Qualitative interviews.	Feasibility (in terms of automatic reports) tested by SQL queries
From capacity to capability: Flexibility	a) Rapid introduction of new products in the existing logistics setup b) > 1 alternative routes through the manufacturing resources c) Follow-up of new products after their release into production d) Operational responsiveness to deviations/disturbances	a) Setup time new products (Kaestle et al., 2017; Soldatos et al., 2016; Wang et al., 2016) b) N/A, acceptable utilization level achieved, large investments needed for further improvements c) Error rate new products (Kaestle et al., 2017; Soldatos et al., 2016; Wang et al., 2016)	a) Yes b) N/A c) Yes d) No

		d) Time between deviation/disturbance and reconfiguration (Bauer et al., 2015; Kaestle et al., 2017)	
Autonomous decision-making and distributed cooperation	a) Autonomous/decentralized re-scheduling b) Integrated interoperable supply chain	a) Auto-reconfiguration error rate (Grundstein, Freitag and Scholz-Reiter, 2017; Rosen et al., 2015; Kaestle et al., 2017) b) Information availability ratio in all relevant network nodes (Leitão, Colombo and Karnouskos, 2016; Ramanathan and Gunasekaran, 2014; Kaestle et al., 2017)	a) No b) No
Unique identification of products and processes	a) Control precision b) Precise responsiveness to deviations / disturbances c) Scope of control	Identification error rate (Soldatos et al., 2016; Whitmore, Agarwal and Xu, 2015)	No
Real-time data acquisition in supply chains	a) Deviations/disturbances are alleviated early with minimal consequences b) Crucial for failure-free decision-making c) Less workload for planners due to eliminated need for time-consuming verification of statuses	a) Time between error occurrence and error ready for handling (Guo, Ngai, Yang and Liang, 2015) b) Data currency (Hazen, Boone, Ezell and Jones-Farmer, 2014; Seitz and Nhuis, 2015) c) Data volatility (Hazen, Boone, Ezell and Jones-Farmer, 2014; Seitz and Nhuis, 2015)	a) No b) Yes c) Yes

Data-to-information conversion	a) Data for actionable decision-making is often available in different formats and acquired from different software b) Relevant data filters for specific roles in the supply chain	a) N/A b) Ratio for necessary data entries at the resource group to total data entries available (Lee, Bagheri and An-Kao, 2015; Lee, Bagheri and Jin, 2016)	a) N/A b) Yes
Resource-pooling and goal congruence	a) Simulation of changes in plans or schedules induced by planners b) Optimal decisions and low amount of resource conflicts on supply chain level	a) Resource utilization, firm level (Pathak, Wu and Johnston, 2014; Schuh et al., 2014; Wang, Wan, Zhang, Li and Zhang, 2016) b) Resource utilization, supply chain / manufacturing network level (Almada-Lobo, 2015; Grundstein, Freitag and Scholz-Reiter, 2017; Schuh et al., 2014)	a) Yes b) No

The paper continues by presenting a broader description of the 12 proposed key performance indicators in the **Table 2** before summing up with a framework for next generation planning and control, based on findings in the case study.

Table 2. Description of key performance indicators proposed in the case study and Table 1.

Key-performance indicator	Description	Effect on improvement of planning and control, estimated by the author and based on the case study results
Setup time new products	Time it takes to set-up all the logistics parameters, associated drawings, tools, and machining programs for a new product in order to get it ready for release into production. The target value should be smaller than a lead-time for	Short set-up times can increase supply chain responsiveness and makes planning and control run faster and error-free in changing supply chain environment.

	raw materials' delivery from supplier.	
Error rate new products	Amount of new products in a given interval of time which are delayed and deviating from the planning schedule due to wrong set-up after their release for production.	This indicator can evaluate the set-up quality of new products as well, as discover reasons for delay. Improvement of set-up before release, ensuring high degree of effective and efficient operations for new products.
Time between deviation/disturbance and reconfiguration	Mean time between deviation / disturbance of planned activities and reconfiguration of the system making it ready for re-execution.	Short reconfiguration times can alleviate negative effect of changes in the system early and before accumulation of consequences to a unacceptable degree. Positive for supply chain responsiveness.
Auto-reconfiguration error rate	Amount of errors causing delays after auto-reconfiguration in a given interval of time.	Low value of this indicator can show that auto-reconfiguration is reliable. High value can urge planners to check reasons for errors or move reconfiguration under the responsibility of humans. Error-free auto-reconfiguration can reduces planning and production costs and increase supply chain responsiveness.
Information availability ratio in all relevant network nodes	Ratio between supply chain / manufacturing network nodes that get relevant information necessary for task accomplishment and total amount of involved nodes	The target value should be 1. Deviation can indicate that automatic information sharing for collaboration purposes is not functioning well.
Identification error rate	Amount of faulty identification of products or operations in a given interval of time.	This indicator can help discover reasons for faulty identification that leads to negative consequences in production flow.
Time between error occurrence and error ready for handling	Mean time between error occurrence and error report available. Target value should be lowest possible.	Short times between error occurrence and error report available for control/action can alleviate negative effect of errors in the system early and before accumulation of consequences to a unacceptable degree. Positive for supply chain responsiveness, costs and effectiveness.

Data currency	Time since the last update of data.	Low value can indicate high synchronization between real- and cyber worlds. High value can indicate that the system is not able to update data frequently as specified. The reasons have to be investigated and requirements for updates adjusted.
Data volatility	Frequency of data updates.	Low value can indicate system instability and a need for data volume, speed and variety check-up.
Ratio for necessary data entries at the resource group to total data entries available	Ratio between information entries necessary to accomplish assigned tasks at the resource and total amount of data visible/available at the same resource.	This indicator can help to isolate the data-noise and to streamline execution of operations, reduce potential for misunderstandings and enhance systems capacity.
Resource utilization, firm level	Specified, acceptable target values for optimal capacity utilization. Widespread use of percentage of working hours available and working hours busy. Trade-off between speed and exposure to uncertainty and costly idle-time.	Enhances possibility to utilize assets or resources effectively and efficiently so as to maximize customer service levels, minimize lead times, and optimize inventory levels in-house. Can result in more predictable planning.
Resource utilization, supply chain / manufacturing network level	Specified, acceptable target values for optimal capacity utilization. Widespread use of percentage of working hours available and working hours busy. Trade-off between speed and exposure to uncertainty and costly idle-time.	Enhances possibility to utilize assets or resources effectively and efficiently so as to maximize customer service levels, minimize lead times, and optimize inventory levels through the supply chain. Can result in more predictable planning.

After having presented and described key performance indicators as a response to emerging requirements for future supply chains in the Industry 4.0 context, the author continues towards constructing a conceptual framework for the next generation operational planning and control at the firm level. The background is obtained from the case study, however, the framework is an initial attempt to raise the discussion among researchers and practitioners, and the detail level is still low. The framework can be considered as adaptable to similar industry applications.

The author considers three fundamental issues that can facilitate companies' roadmap for improving and adapting existing planning and control practices. These are: a) Utilization of existing technologies, resources and routines; b) Necessary investments in technology and resources; c) Changing of manufacturing models in order to facilitate planning and control. The framework is presented in **Figure 3**.

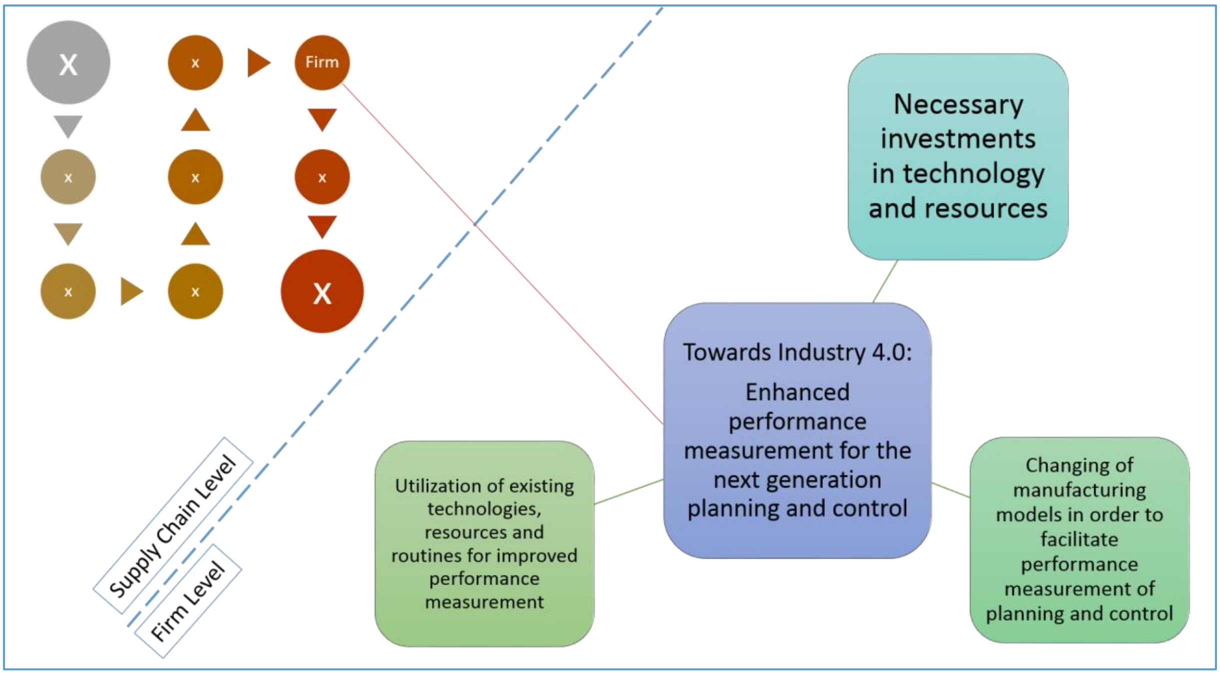

Figure 3. A conceptual framework for the next generation operational planning and control at the firm level. Similar improvement efforts should be carried out in a coordinated way at the rest of the supply chain nodes in order to achieve supply chain integration and interoperability.

The framework is explained as follows. The focus is on the firm level enhancements and improvements, however these should be extended to the supply chain or manufacturing network levels in order to multiply the effect of improvement and achieve higher integration and interoperability.

Utilization of existing technologies, resources and routines for improved performance measurement is considered as the starting point as this effort is achievable by fine-tuning the existing situation with minimal investments and changes of firm strategy or production model. The case study shows that 6[1] of proposed 12 key performance indicators are readily available through auto-generated reports for analysis and improvement purposes. People, the ERP-system and user interfaces can be adapted quickly and with minimal effort.

Changing of manufacturing models in order to facilitate performance measurement of planning and control is another domain for management consideration. Automation, autonomy and changing control hierarchies are important issues in this case as balancing between them defines risks and roles associated with human-machine interaction. Increasing degree of automation and autonomy facilitates, among others, automatic real-time reporting which is available at control centers where people can control the situation and interfere when necessary. Barriers for implementation are often associated with the company's wish to manage risky decisions (large potential for negative consequences) manually. Auto-reconfiguration error rate as a performance indicator is therefore not feasible yet. However,

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[1] Setup time new products, Error rate new products, Data currency, Data volatility, Ratio for necessary data entries at the resource group to total data entries available, and Resource utilization at firm level.

autonomation, as mentioned before, is one of the core concepts of Industry 4.0 and should therefore be taken in management's plans in order to meet the emerging requirements.

The last issue considered in the framework is *necessary investments in technology and resources*. In the context of next generation performance measurement for planning and control, this is directly associated with measurability. 6[2] key performance indicators of the proposed 12 require sensors, ID-extensions, readers and new reporting algorithms in order to be feasible for performance measurement. This means that investments are necessary and should be a part of both, short and long-term firm strategy of digitalization.

CONCLUSION AND FURTHER RESEARCH

This paper has presented the emerging strategic requirements for next generation, digitalized supply chain management in the Industry 4.0 context. These requirements were then converted to the operational level and linked particularly to the process of operational supply chain planning in the ETO-manufacturing environment. The research question was how operational supply chain planning can be controlled and improved while both, utilizing available technologies and resources, and keeping the linkages to companies' digital strategies intact. 12 different new or redefined key performance indicators have been identified in our classification, in contrast with the 2 indicators that were already used in the case company. Ultimately, a simple firm-centric framework for the next generation performance measurement in operational planning and control was presented. The framework addressed three main issues: a) Utilization of existing technologies, resources and routines; b) Necessary investments in technology and resources; c) Changing of manufacturing models in order to facilitate planning and control. However, the framework and proposal of the performance indicators are considered as an initial attempt to raise the discussion among researchers and practitioners, and the detail level is still low.

An analysis of research within fields of Industry 4.0 and performance measurement in supply chains and operations confirms that research is predominantly heuristics-based (scheduling literature) and there is lack of both, empirical studies and systematic approach to performance measurement for planning and control in the Industry 4.0 and ETO-context.

This paper highlights further directions for research focused around three themes: a) Operationalization of emerging requirements for supply chains in the Industry 4.0 context; b) More empirical research on planning and control performance measurement, including testing of new or redefined key performance indicators; c) Extension of operational planning and control performance measurement from firm-level to supply chain or manufacturing network level.

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[2] Time between deviation/disturbance and reconfiguration, Auto-reconfiguration error rate, Information availability ratio in all relevant network nodes, Identification error rate, Time between error occurrence and error ready for handling, Resource utilization, supply chain / manufacturing network level.

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