Framework for a Cost-Benefit Analysis of Lean Production Systems

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Abstract

Although lean production and its advantages are discussed for over 20 years, the detailed identification of the contribution of individual lean methods is still hardly possible. Due to the lack of efficiency analysis frameworks the benefits and costs of a lean production system remain vague in literature. This paper presents a framework to analyze the benefits and costs of the implementation of lean methods. A specific decomposition methodology is used which starts with a high-level performance indicator to break it down to operational indicators which individual lean methods can be assigned. The framework assists companies to track the contribution of individual lean methods to a key performance indicator.

1 Introduction

The concept of lean production systems (LPS) has been discussing for a long time in entrepreneurial practice and particularly in the scientific field (see e.g. Uygun et al. 2015; Uygun et al. 2011; Uygun et al. 2009;). Lean is nowadays even seen as a standard requirement by customers in terms of large companies (Reynolds & Uygun 2017). Many companies have adapted the concept to their company-specific situation and could achieve considerable positive effects (see e.g. Uygun et al. 2010). Improvements in indicators like higher productivity, cost reductions, better work conditions, set-up time reduction, flexibility, stock reductions, shorter lead times, or elimination of waste are reported (Liker, 2004; Ohno, 1988; Shingo, 1992). In addition to these qualitative statements, quantitative results have been published sporadically by users of lean production systems after implementing them. Double-digit percentage improvements in indicators like lead time, inventory, required space, and productivity are stated.

The absence of a uniform system based on performance metrics for the assessment of the effects and economic efficiency of implementing an LPS impedes the comparability of the achieved results. Traditional performance metrics are partly even unsuitable to transparently represent the changes which are caused by LPS. Moreover, it can be criticized that merely the "success stories" are published and negative concomitants are ignored or trivialized in publications. After all, it is to assume that failures or problems in internal change processes are only reluctantly presented by companies in public.

Nevertheless, the facts that lean production systems increasingly diffuse and that such systems are usually applied by very competitive companies indicate, at least indirectly, upon their competitive relevance. Therefore, it is appropriate to register the effects of the application of LPS by means of a holistic score system in order to be able to track in detail the effects of implementing lean methods.

It has to be stated, that the mere focus on key performance indicators is not expedient since the specific contribution of individual lean methods cannot be tracked. So, a framework is necessary which allows the identification of the contribution of individual lean methods.

For this purpose, an LPS-specific performance metrics system is presented in this paper. With the help of this system, the effects of LPS can be clearly comprehended. Here, the efforts refer primarily to the implementation phase, whereas the benefits arise not until the operating phase. Nevertheless, efforts also arise in the operating phase due to continuous efforts for improvement.

2 Literature review

Dealing with the development of a framework for efficiency analysis of the implementation and application of lean methods in production systems, a systematic approach is needed. There are some kinds of frameworks in literature which are presented and evaluated in the following. According to the initially described situation following criteria are crucial for the needed framework which all other existing frameworks will be evaluated against:

- tracking of the contribution of individual indicators and
- focus on lean production.

Besides some implementation guides (Keßler & Uygun 2007; Kortmann & Uygun 2007; Uygun & Straub 2011; Uygun & Wagner 2011) there exist frameworks dealing with the evaluation of efficiency and performance. Here, especially performance measurement systems are of interest. For the scope of this paper it can be distinguished between general performance measurement systems and lean-specific performance measurement systems.

There exist several performance measurement systems, like the Balanced Scorecard with its four perspectives (Kaplan and Norton, 1992), the Performance Prism with its five perspectives (Neely et al., 2001), the Integrated Performance Measurement System with its integration of four hierarchically aligned business levels (Bititci et al., 1997), the SMART Pyramid with its internally and externally focused measures of performance (Cross and Lynch, 1988), the Performance Measurement Matrix with its external and internal dimensions (Keegan et al., 1989), the Results and Determinants Framework with the distinction of two types of performance measures (Fitzgerald et al., 1991), performance measurement system for inter-organizational collaborations (Uygun & Schmidt 2011) or the Inputs, Process, Outputs, and Outcome Framework with four stages of performance measures (Brown, 1996). Apart from these performance measurement framework there also exist relevant collaborative frameworks, like the Three Elements Framework with three kinds of measurement (Parung and Bititci, 2008), the Performance Measurement System linked to Enterprise Networks with its three dimensions (Saiz et al., 2007), the Collaborative Index with three interrelated dimensions (Simatupang and Sridharan, 2004) or the Antecedent-Process-Outcome Model (Wood and Gray, 1991). Each framework has distinct differences compared to the others. In general, these one are systematic approaches with the possibility of tracking the contribution of specific performance indicators, but they do not focus on lean methods.

There are several concepts especially for lean production available which deal with the analysis of the benefits and costs. Meade et al. (2006) examined the impact of using accounting methods for the calculation of profits in the implementation efforts of lean production systems which turn out to be negative by using a hybrid multi-period simulation for manufacturing planning and inventory tracking. Even efficiency gains through lean methods concerning reduction of inventories cannot reduce that negative impact. This approach has a strong financial focus on the negative impact of accounting methods without considering in detail the benefits and costs of lean methods.

Abdulmalek and Rajgopal (2007) analyzed the specific benefits of lean manufacturing in a steel mill applying value stream mapping and simulation. In this specific case they come up with a comparison of the production processes before and after lean production. However, this contribution offers merely general benefits of the introduction of lean methods, like the reduced production lead time or lower work in process inventory. A specific framework or approach for the overall contribution of each lean method is missing.

Ruiz-de-Arbulo-Lopez et al. (2013) also criticized the shortcomings of traditional cost accounting methods and present in their paper the value stream costing as technique for analyzing the performance of the implementation and deployment of lean methods. Yet again, this contribution has a strong financial focus.

Melton (2005) analyzed the benefits of lean manufacturing in process industries. Here, a general and rather qualitative and strategic analysis is conducted. The operationalizing of the benefits in terms of depicting the contribution of each single lean method is missing. The costs and efforts are also not in the focus of this paper.

On the other hand, there are existing frameworks for assessing lean production systems which merely focus on the effectiveness and not on the efficiency. Examples are the Rapid Plan Assessment (RPA) as a framework for a quick analysis of the production system based on a physical inspection of the production system according to eleven evaluation groups (Goodson, 2002), Operations Excellence Audit Sheet based on RPA with four additional evaluation groups (Alfnes et al., 2008), Framework for a Lean Manufacturing Planning System based 17 metrics groups in four evaluation categories process flow, quality, financial, and productivity (Mejabi, 2003), and 20 Keys as a self-assessment tool to evaluate the maturity of the application of a lean production system based on 20 action fields (Kobayashi, 2000). Although these frameworks and approaches are lean-specific they do not focus on the efficiency analysis of lean production.

So, it can be stated that there is no existing approach dealing with the problem of automatically assisting and enabling the analysis of efficiency of lean production systems.

3 Development of a Methodology

There is a need for a framework which enables companies to track the contribution of each single lean method in order to conduct an efficiency analysis of the implementation and application of a lean production system. For the development of such a framework, a methodological approach is necessary.

The methodology that allows such tracking consists of following steps:

1. Definition of an overall approach
2. Specification of the approach
3. Identification of indicators
4. Assignment of lean methods to the indicators

Firstly, the overall approach of the framework has to be chosen. As mentioned before, the framework has to allow the tracking of the specific contribution of each method. In such cases, the deployment of decompositions is practical.

Secondly, the decomposition has to have a starting point. Based on a composed key performance indicator, like profit or return on investment, the indicators can then be broken down till operational indicators. Here the return on investment (ROI) is expedient as specific investments are to be done in order to implement a lean production system and whose benefits can then be weighed against the investments.

Thirdly, the dependent indicators derived from the ROI have to be identified. This will be done through extensive literature review so as to detail the indicators. In the end, a comprehensive framework with a detailed decomposition of indicators will be developed which enables the identification of the contribution of specific lean methods to the return on investment. In the following, the development of this framework is presented in detail.

Eventually, the lean methods will be assigned to the framework. Due to the huge number of existing methods in the context of lean production systems, in the following only exemplary methods will be assigned to the broken-down indicators.

4 General Framework

As initially mentioned, the companywide implementation and the sustainable operation of a coordinated and modern lean production system contribute to simultaneous improvements in the dimensions of quality, time, and cost, and accordingly to improvement of competitiveness. So, to systematize the effect, this fact is used as an opportunity to elaborate on how these dimensions can be influenced by LPS. So, a detailed decomposition begins with the mentioned top performance indicator ROI (Uygun 2013).

In general, it has to be noted that quantification of the benefits of specific lean methods is difficult to realize. With regard to differences in company size, industry, and country, also, no universally valid quantitative evaluation scheme can be compiled. Instead, LPS depend on company-specific conditions. Yet, a qualitative statement concerning the advantageousness is always possible. For that reason, the framework is qualitatively described in the following. The benefits and investments are considered for a company which is interested in implementing an LPS. In addition to this, it is explained how a company can increase the return on investment by means of improving the indicators in the field of quality, time, and cost savings and which investments in detail are necessary for this. The aspects which are presented here are to be perceived as guidelines which have to be projected in a further step on company specifics in order to facilitate company-specific, quantitative statements.

<table>
<tr><td colspan="4">return on investment</td></tr>
<tr><td colspan="3">profit</td><td rowspan="4">investments</td></tr>
<tr><td colspan="2">increase in customer satisfaction and sales in existing markets</td><td rowspan="2">reduction of costs</td></tr>
<tr><td>quality assurance of services</td><td>fast delivery</td></tr>
</table>

Table 1: The general framework

In Table 1 the general pattern of the decomposition is presented. It is recognizable that in general profit can be increased by improving the parameters quality (quality assurance of goods and services), time (fast deliveries), and expenses (reduction of costs). Based on the general profit formula (profit = turnover - costs), customer satisfaction can on the one hand be increased by improving quality and time (procurement lead time, lead time and distribution time) (Cochran and Dobbs, 2001). As a result of this, a closer connection between customer and company is established and consequently more intensive business contacts or repeated and increased purchases of the customer can occur. On the other hand, the company can also increase profits by minimization of its internal expenses when sales are constant. The decomposition of the investments refers to the implementation efforts for the particular lean methods.

5 Decomposition for Effect Analysis

5.1 Effects on Quality

With regard to the dimension quality, an LPS often makes directly a contribution to success by means of specific elements and methods of quality management, like quality control loops, quality stop, SPC, process FMEA, quality agreements, poka yoke, etc.. Thus, the Toyota Production System comprises for example the element 'Total Quality Control', in the Mercedes Production System it is referred to the subsystem 'quality and robust processes' plus three corresponding production principles, and the Audi Production System contains the element 'quality processes'. These elements go well together with the quality management systems which are already implemented in most companies and integrate those into a superior methodical framework. By means of stable and robust processes a continuous high product quality is achieved in order to increase customer satisfaction (see Table 2). In addition, further elements of an LPS contribute indirectly to the quality improvement by means of existing cross-linkages as well. For example, measures for visualization and standardization or methods concerning work organization, like 5S. Thus, the quality characteristic values are positively affected. The striving for continuous improvement, which is one of the foundations of an LPS, implies that the status quo regarding quality as well as the two other target dimensions is constantly questioned and optimized.

As to the decomposition of benefit, the impacts of the particular influencing factors on the quality assurance concerning services are significant (see also Table 2). Quality assurance is achieved through the reduction of variation in quality on the one hand, and of quality improvement on the other. The latter can be divided into the improvement of product quality along with service life, safety, and functional efficiency, and into the improvement of process quality along with the improvement of service competence and service constancy. The reduction of variation in quality is divided into the reduction of product deviations and process deviations. The former are attained by minimizing deviations or disruptions due to employees, machines, methods, material, environment, and measurability, which can be prevented by means of certain methods. The reduction of process deviations is divided into the reduction of errors concerning input and output.

<table>
<tr><td colspan="4">quality assurance of services</td></tr>
<tr><td colspan="2">improvement of quality</td><td colspan="2">reduction of variation in quality</td></tr>
<tr><td>improvement of process</td><td>Improve-ment of</td><td>reduction of process</td><td>reduction of product deviations</td></tr>
</table>

quality		product quality			deviations							
improvement of service loyalty	improvement of service capability	functional efficiency	security	service life	reduction of errors concerning output	reduction of errors concerning input	reduction of deviations due to measurability	reduction of deviations due to environment	reduction of deviations due to material	reduction of deviations due to methods	reduction of deviations due to machines	reduction of deviations due to employees

Table 2: LPS-specific decomposition of the quality dimension

Lean methods, like “immediate failure checking“, “standardized and transparent work sequences“, “flexible employment of workers“ and “standardized resources“, enable for example the reduction of deviations caused by employees, which contribute to the reduction of product deviations. Those reduce quality deviations and can therefore lead finally to the quality assurance of services. Due to the quality assurance of services, sales can be stabilized and increased in existing markets. This contributes to profit increase and therefore improves the return on investment (see Table 2 in combination with Table 1).

5.2 Effects on time

The factor time is influenced by the interplay of the elements of an LPS as well. The striving for elimination of waste entails the examination of value creation and the identification of value-adding and non-value adding processes. Non-value adding processes can be divided into planned supporting processes, like changeover or transportation, and unplanned blind processes, like rework. While loss of time due to blind processes should be eliminated for example by means of continuous improvements or Poka Yoke, other methods, like Single-Minute Exchange of Die (SMED) and work in interdisciplinary teams, contribute to the optimization of inevitable supporting processes. This is achieved by analyzing processes from different perspectives and subsequently reducing them to the essential procedures as well as challenging and improving them constantly (Shingo 1989). The flow-oriented restructuring of the value stream serves the realization of a waste reduced linkage of individual value-adding processes as well and serves therefore also the foreshortening of the transition periods. The value-adding processes can possibly be advanced by means of applying specific lean methods. However, the production process should be considered in a holistic way rather than putting the primary focus on the application of single lean methods. Thus, it can happen that the duration of the actual value-adding process is increased in order to achieve a reduction of the overall lead time by means of applying easier but more flexible machines, which concede smaller batches and shorter waiting periods due to lower setup times. Due to the gained flexibility, it is possible to synchronize the actual value creation with the customer demand and to avoid waste by overproduction in consequence of big batch sizes. In addition, the planned processes are made foolproof by means of intelligent automation solutions or Poka Yoke in order to avoid the occurrence of defects. In this manner as well, lead times (and also quality) are optimized, and finally costs can be reduced.

The LPS-specific decomposition of the time dimension is depicted in Table 3. Punctual and quick deliveries are achieved through the reduction of procurement time, systematic reduction of lead time, and the reduction of distribution time.

fast delivery		
reduction of procurement time	systematic lead time reduction	reduction of distribution time

Table 3: LPS-specific decomposition of the time dimension

The procurement time can be decreased by means of faster inquiries, reduction of offer processing time, reduction of negotiation time, faster ordering decision, more efficient purchasing, faster order confirmation, and faster delivery (see Table 4).

reduction of procurement time						
faster inquiries	reduction of offer processing time	reduction of negotiation time	faster ordering decisions	more efficient purchasing	faster order confirmation	faster delivery

Table 4: Decomposition of procurement time reduction

Lead time consists on the one hand of interoperation time and of execution time on the other. A reduction of interoperation time is achieved through reduction of waiting time, transport time as well as control time. The waiting time can be reduced by a decrease of intermediate storage time, process-based waiting time, disruption-based waiting time and employee-induced waiting time. Here, the reduction of disruption-based waiting time is realized through faster troubleshooting and a systematic prevention of disruptions. The reduction of execution time can be divided into the reduction of processing time and the reduction of setup time. The former is influenced by the determination of cycle time, supply in cycle time, and adjustment of takt time. The latter can be further divided into the adjustment of machine times and adjustment of employee times. The reduction of setup time, which is the second determining factor of execution time, is achieved through the definition of optimal batches and the product mix improvement.

<table>
<tr><td colspan="12">systematic lead time reduction</td></tr>
<tr><td colspan="6">reduction of interoperation time</td><td colspan="6">reduction of execution time</td></tr>
<tr><td colspan="4">reduction of waiting time</td><td rowspan="2">reduction of transport time</td><td rowspan="2">reduction of control time</td><td colspan="3">reduction of processing time</td><td colspan="3">reduction of setup time</td></tr>
<tr><td>intermediat</td><td>process-</td><td>disruption-based waiting time</td><td>employee-</td><td>determinati on of cycle</td><td>supply in cycle time</td><td>adjustment of takt time</td><td>definition of optimal</td><td>product mix improvemen</td><td>optimization of setup</td></tr>
</table>

Table 5: Decomposition of the systematic lead time reduction

In addition to the described reduction of procurement time and the systematic lead time reduction, the factor time can be further minimized by the reduction of distribution time. Storage, transport, and handling are the determining factors of distribution. A reduction of storage is achieved through a shorter storage period, faster order picking, faster packaging, faster palletizing, and faster provision. Faster transportation is based on reduction of unloaded trips and optimization of loaded trips. Handling is determined by transport time to forwarding, merging and sorting, packaging and labeling, compaction and sealing, dispatching, and loading of the transport vehicles. The fast realization and processing of these components result in faster handling.

reduction of distribution time												
storage					transport		handling					
shorter storage	faster order picking	faster packaging	faster palletizing	faster provision	reduction of unloaded	optimization of loaded transport	shorter transport time to	faster merging and sorting	faster packing and labeling	faster compaction and sealing	faster dispatching	faster loading of transport vehicles

Table 6: Decomposition of the distribution time reduction

For example, “elimination of waste” as a lean method can accelerate dispatching, what makes prompt and fast handling possible. Through this, the delivery or distribution time can be reduced, that then leads to a fast or accurate delivery. Thus, customer satisfaction and sales can be increased, what is reflected in profit and consequently in the ROI (see Table 6 in combination with Table 3 and Table 1).

5.3 *Effects on costs*

The exact quantitative effects of the application of an LPS on the costs of production are hardly to be determined due to the lack of specific calculation methods for production systems. The long-term nature and the interconnection with which the initiated measures become effective are reasons for this. Many activities of an LPS manifest themselves primarily in changed process key indicators like lead times, inventories, or an increased motivation among employees. These improvements lead indirectly to savings. Nevertheless, it is difficult to show these in traditional cost accounting systems in order to link specific achievements to particular methods or even to prove quantitatively the advantages of the interaction of different methods. Hence, there exist a few published calculations of the positively estimated cost effectiveness of particular measures only, e.g. for Kanban or Just in Sequence. Qualitative statements about changes in the cost structure can be made any time by means of a causal chain analysis of the effects of particular elements in an LPS. These measures are reflected in the minimization of process, structural, and capital costs. Process costs comprise the diverse field of cost elements which are linked to the development, value-adding and control processes, while the structural costs enclose the cost positions which are influenced by production, product, and resource structure. Capital costs arise for fixed and current assets.

By means of a detailed decomposition of the costs, which is depicted in Table 7, the costs can be reduced by elimination of waste of elementary and managerial production factors. The production factors form the basis for production, which can be considered as input. Elementary production factors are directly involved in production and are work equipment, tools, organizing tools, stock, space, and physical work. The managerial factors are indirectly involved in production and generally comprise planning, organization, and controlling. The particular production factors are defined more closely by means of their effectiveness, efficiency, and integration into the overall context.

<table>
<tr><td colspan="21">cost reduction</td></tr>
<tr><td colspan="18">elimination of waste of elementary factors</td><td colspan="3">elimination of waste of managerial factors</td></tr>
<tr><td colspan="4">elimination of waste of work equipment</td><td colspan="3">elimination of waste of tools</td><td colspan="3">optimal deployment of organizing systems</td><td colspan="3">reduced stock</td><td colspan="2">reduced space</td><td colspan="3">Elimination of waste of physical work</td><td rowspan="2">application of effective methods</td><td rowspan="2">efficient operation methods</td><td rowspan="2">stable information exchange</td></tr>
<tr><td>high utilization</td><td>failure-free processing</td><td>less energy consumption</td><td>optimal linkage</td><td>optimal dimensioning</td><td>durable units</td><td>interoperability in logistics</td><td>application of effective media</td><td>less energy consumption</td><td>avoidance of media discontinuity</td><td>avoidance of overproduction</td><td>efficient usage of stock</td><td>optimal line balancing of processes</td><td>efficient use of given space</td><td>optimal arrangement of space</td><td>efficient (multi-)deployment</td><td>efficient movements</td><td>reduction of coordination problems</td></tr>
</table>

Table 7: LPS-specific decomposition of the cost dimension

For example, the lean method "standardized resources" facilitates the reduction of coordination problems. This contributes to the elimination of waste of physical work by which waste of elementary factors can be avoided and costs can be reduced. Through this, the profit and thus the ROI can be improved (see Table 7 in combination with Table 1).

In addition to the already mentioned positive results, the implementation of lean methods leads to further positive results, of which the effects on the dimensions quality, time, and costs are hardly verifiable. One result, which should not to be underestimated, is, e.g., the better impression which customer and supplier get of a company in which value creation of particular components is produced in an easily comprehensible way by means of a continuous flow. If, in addition, the employees are integrated into the elaboration of the process of change, it is expectable that numerous measures indirectly contribute to an increase in motivation.

Beyond the LPS-specific decomposition of the benefit concerning the introduction or implementation of an LPS, which has been presented in this chapter, the investments for introduction of an LPS have to be considered, too, in order to be able to conduct an efficiency analysis. For this purpose, a decomposition of the investment is deduced in the following.

6 Decomposition for Investment Analysis

After deriving the indicators for defining the benefits of the implementation of a lean production system, the same procedure has to be done for the other side of the coin. For decomposition of the investments a systematic approach is once again needed. In contrast to the effects analysis the analysis of the investment efforts needs another approach. For this, following methodological approach is expedient:

- Define investment objects
- Specify investment objects
- Define investment types
- Assign investment type to objects

Firstly, the decomposition of the investment focuses in particular on lean methods and their implementation. To implement lean methods investments in resources in terms of production factors have to be done. For this, it is appropriate to divide the specific investment objects in production factors (physical work, work equipment, tools, organizing tools, space, stock and services).

In a second step, these resources have to be further specified in order to define the particular investment. The characteristics of the defined resources have to be outlined.

Thirdly, investment types have to be defined, which are necessary for the implementation and successful application of lean methods. Based on an extensive literature review as to lean production all relevant investment types for implementing lean methods are gathered and grouped, which then are discusses with company representatives in order to verify their accuracy. Following investment types are agreed upon:

- Qualification (Q)
- Purchase (P)
- Implementation (I)
- Adaptation (A)
- Maintenance (M)
- Standardization (S)
- Replanning (RP)
- Rescheduling (RS)
- Optimization (O)

Eventually, these investment types have to be assigned to the investment objects. In this paper, this is done only schematic. The following Table 8 shows an exemplary assignment.

		element 1			element n			
resources	***characteristics***	method 1	component 2	component 3	component 4	component 5	component 6	component n
physical work	indirect employees		Q		Q		Q	
	direct employees		Q					
work equipment	machines and facilities							
	modes of transport		P					
	storage system		P				P/A	
tools	planning tools							
	technical tools							
	management tools		P/A					
	control tools							
	transport devices		P/A				P/A	
	storage equipment							
stock	intermediate stock							
	inventory							
space	work space							
	storage area							
	special area							
organizing tools	software							
	hardware							
services	supplier concepts		O		O		O	
	distribution concepts						O	

Table 8: Matrix of investment costs for the components of a LPS

An analysis based on this system facilitates a clear depiction of the necessary investment and provides a basis for the calculation of the costs for the purposes of implementing lean methods. By means of considering the benefit which arises from the implementation of an LPS, an assessment of the economic efficiency of the LPS can be conducted.

7 Conclusion

The systematically developed framework for the efficiency analysis of the implementation of lean methods enables companies to clearly track the specific contribution of each individual lean method to the key performance indicator ROI. In addition, on the basis of this systematic framework companies are enabled to quantify the success of an LPS. The framework allows the understanding of the success of an LPS, which has hitherto often been explained in a very vague way in literature.

This framework has to be customized in a further step in order to be able to depict the company-specific benefits and investment costs of the implementation and application of lean methods. For this, the company-specific lean methods have to be identified in a first step. On this basis, the contribution of each individual lean method has to be worked out. Here, a group discussion with persons in-charge of these methods offers a profound basis. Afterwards, the investment types of the company-specific lean methods have to be assigned to the resources.

It has to be stated that the decomposition of benefits is qualitative. The quantification is based on company-specific conditions. In some cases the quantification of several indicators is not possible. On the other hand, the investments can be calculated. But the quantification in terms of costs also depends on company-specific factors.

For reasons of simplification merely one-dimensional considerations concerning the effects of exemplary elements of a lean production system are made. In reality, the manifold measures interact and provide for a synchronous optimization of the three dimensions.

In future, this framework may be adapted to the needs of networked manufacturing (see e.g. Besenfelder et al., 2013; Güller et al., 2015) as well as intelligent and advanced manufacturing systems (see e.g. Reynolds & Uygun, 2017; Karakaya et al., 2016).

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