Systematic Support for Continuous Optimization of Lean-Based Manufacturing Systems

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Due to the organizational complexity that goes along with the introduction and application of a lean production system, companies cannot lift the full potential of lean production. Problems, such as specific company conditions, lack of expertise in the implementation and continuous development as well as financial and personnel constraints inhibit the introduction and in particular the use and sustainable development of methods of lean production. As part of the continuous improvement process the constant questioning of existing structures is of particular importance. However, companies are missing tools that support automatically the development of lean production systems so that their full potential can be exploited. Against the background of the described problem, the author developed a tool in the form of an optimization system for lean production systems and validated it in an automotive supplier, which allows a comprehensive analysis of the current state of the application of lean methods and the proposal of relevant suggestions taking into consideration the diverse interrelations in the network of interdependent lean methods. An extensive record of existing basic and method parameters paired with a comprehensive assignment of optimization measures allows a consistent display of improvement proposals which can be applied within the continuous improvement process. The target group of this system is goods manufacturing industry.

Keywords: Lean production, diagnosis, evaluation, improvement, continuous improvement process

Motivation

Even after almost 30 years, the implementation and improvement of lean production systems are still of interest, as shown in several studies, like Uygun et al. (2009), Uygun et al. (2010). The change of the production organization towards a waste-free and flow manufacturing implies major changes in the configuration and coordination of production systems which is still a big challenge for companies. The once implemented methods need a continuous development in order to become steadily better. Especially for this case, companies are lacking support to realize a continuous improvement of the lean production system they once set up. This results in disappointment of lean production systems which normally could generate immense efficiency gains, if they are implemented and developed properly.

For the continuous improvement companies rely more and more on experts, especially consultants, which have implicit knowledge of the complex linkages of a lean production system. Since, the improvement process should be continuously, the support should also be continuously.

So, the challenge is to develop an optimization system which continuously supports companies to question their lean production system. The evaluation system should therefore give automatically company-specific recommendations rather than general recommendations for improving the lean production system.

Existing Concepts

After successfully implementing lean methods of a lean production system, be it within companies (e.g. Kortmann & Uygun 2007, Keßler & Uygun 2007, Uygun & Wagner 2011) or across companies (e.g. Uygun & Straub 2011, 2013), their continuous improvement has to be considered. Such an optimization system has to comprise both an evaluation and recommendation aspect. The former is very present in literature whereas the latter is underrepresented.

There are concepts for the optimal deployment of lean production systems, like the ones by Kosonen and Buhanist (1995), Ahlstrom (1998), Spear and Bowen (1998), Liker and Meier (2006), Sakai et al. (2007), Black (2007), or Wilson (2010). Additionally, there are also guidelines for specific lean aspects available, like the ones by Jugulum and Samuel (2008) as well as Thomas et al. (2009) who concentrate on the implementation of Six Sigma, whereas Mothersell et al. (2008) have a special focus on hoshin kanri. Apart from that some authors worked on the implementation in specific industries as case studies, like Kojima and Kaplinsky (2004) focusing on automotive suppliers, Kumar et al. (2006) focusing on Indian SME, Lee and Jo (2007) adopting lean principles to a big car manufacturer, Collins and Muthusamy (2007) implementing lean methods to a healthcare provider, Ben-Tovim et al. (2007) deploying lean methods in a hospital similar to Young and Wachter (2009), and Rutledge et al., (2010) applying lean methods in research laboratories. However, all these approaches address an efficient and optimized deployment of lean production systems, but they propose merely implementation guidelines without discussing the continuous development.

Some other authors analyzed the results of the implementation which can be seen as an evaluation of the current state. Bamber and Dale (2000) examined an aerospace manufacturing organization as to weaknesses and differences to motor manufacturing environment in the context of the deployment of lean methods. Cuatrecasas (2002) evaluated the variability of performance of adopting lean principles to service processes. These approaches purely state the effects of lean production systems without developing a systematic methodology for optimization.

Nevertheless, there are standardized and widely acknowledged evaluation methods, like the Rapid Plant Assessment by Goodson (2002), Operations Excellence Audit Sheet by Alfnes et al. (2008), Framework for a Lean Manufacturing Planning System by Mejabi (2003), Value Stream Mapping by Rother and Shook (1999), and the 20-Keys Methodology by Kobayashi (1995). These approaches offer different perspectives as to company performance and are depicted in the following.

The Rapid Plant Assessment (RPA) by Goodson (2002) is a general lean audit to check the degree of fulfillment of lean principles based on visual impressions and interviews during a shop floor tour in a relatively short time with an assessment scheme and questionnaire. Although the RPA is suitable to assess the realization of maturity of lean principles and methods, the evaluation is strongly subjective and can be seen as rough due to the limited measurement catalog.

Similar to the RPA a further approach by Alfnes et al. (2008) is available which is called the Operations Excellence Audit Sheet for assessing the maturity of the production system. This instrument is also suitable for determining the maturity of implementation of lean principles and methods. However, there is no detailed description of the characteristics of each stage and the documentation needed for operationalization in the form of checklists, making the assignment to the respective grades highly subjective. Although the approach provides an analysis of weaknesses, but does not (automatically) derive improvement measures.

Apart from that, there exist the Framework for a Lean Manufacturing Planning System by Mejabi (2003) which encompasses an assessment methodology for both the actual state of the production system and the lean implementation in the form of "Cost of Waste" to quantify the wastes, "Cost of Lean" and "Lean Savings" to determine the lean manufacturing cash flow for the analysis of material costs and profits of a lean implementation and development. A standardized set of lean metrics has been developed that measures the company performance. In addition, the concept also includes a lean manufacturing scorecard and a benchmarking module. These assist companies in the performance measurement and determine the medium-term goals, which extend to a planning horizon of up to five years. This approach includes planning, assessment as well as improvement methodology of lean manufacturing and is well suited to assess the progress of implementation of the principles by assessing the achievement of objectives and performing an economic efficiency analysis. The main focus of the approach, however, lays on the medium-term planning horizon and the management level.

As a further general evaluation and optimization instrument the Value Stream Mapping (VSM) by Rother and Shook (1999) can be stated. Based on production data and shop floor visits a current state map with weaknesses is derived which leads to the design of a future state map. This approach takes into account the whole production system and the main material flow on a rough level and gives hints for the general redesign of the production system. A detailed discussion about the effective and efficient deployment of lean methods is not considered. Sullivan et al. (2002) examine an equipment replacement decision problem using this Value Stream Mapping. They develop a roadmap to extract necessary information for analysis of equipment replacement decision problems from VSM.

There exist also the 20 Keys® method by Kobayashi (1995) which is a qualitative benchmarking approach and includes a self-assessment system, which makes it possible to assess the status quo and the implementation stages of the production system and compares them with best-practice companies. In 20 different areas criteria are established, which greatly influence the evaluation of a production system in the company. All keys influence each other, so that a system of mutual interdependence is set up. The 20-Key system is suitable for benchmarking of lean production systems but it focuses rather on the evaluation of lean principles. Although the 20-Key system includes individual methods, the detail level of the checklists is not enough for an in-depth assessment of methods. An automated display of recommendations is not possible. The derivation of improvement actions must be performed manually.

Doolen and Hacker (2005) developed a survey instrument to assess the number and level of implementation of lean methods in a company. They also conducted an exploratory study in the electronics industry and found out that many lean methods are deployed but with different levels of implementation which is mainly caused by economic, operational, and organizational factors.

There are also industry and company-specific approaches for efficiency analysis, like the ones by Wang (2008) and Saurin and Ferreira (2009). The approach of Wang (2008) deals with the efficiency analysis of lean methods based on a case study of an optic enterprise with its different factories. The methodology is based on empirical data which make obvious that efficiency is mainly affected by the organizational culture. This approach is too rough-cut and company specific so that a general analysis can hardly be done. The analysis focuses on weaknesses without giving countermeasures automatically. Saurin and Ferreira (2009) analyzed the impacts of lean manufacturing on working conditions of a harvester assembly line in Brazil based on a qualitative assessment, questionnaire, and feedback meeting of the implementation of lean methods through personal interviews with managers, safety specialists, and workers. The framework for analysis comprises the four aspects work content, work organization, continuous improvement, and health and safety. This framework is company specific and too rough for an in-depth analysis. The proposal of improvement measures is also lacking.

Furthermore, there is the concept of Meade et al. (2006) analyzing the negative impact of accounting methods on profits while implementing lean methods. This impact on profit is calculated by common accounting methods. They found out that the efficiency gains by a lean production system with continuous reduction of inventories do not lessen that negative impact. They conducted a hybrid multi-period simulation approach for manufacturing planning and inventory tracking. They use a spreadsheet program for generating MRP data and a simulation software for the model production environment in order to examine the magnitude and duration of that negative impact. This approach has a strong financial focus on the negative impact of accounting methods without considering improvement measures for lean methods.

In addition to the assessment of a lean production system in its entirety, there are also specific audit approaches for individual methods developed by and used in industry, such as group work, standardization, continuous improvement, or 5S, which only focus on one specific method. Therefore these audits are not suitable for the evaluation of a lean production system in its entirety.

Summing up, existing implementation approaches address the optimal deployment but are lacking a continuous development component. The analyzed evaluation systems, on the other hand, come as audits and/or maturity models. Audits are well suited for lean production, however, there is a low grade of detail of the existing approaches and necessary adjustments to these standardized evaluation methods have to be considered. The quality of the results of the evaluation depends highly on the quality of the assessment catalog. There also exist the general disadvantages of audits, such as the restriction to a purely qualitative evaluation and certain subjectivity. Apart from that, there are maturity models which are well suited for lean production, but the applicability of an evaluation catalog must be created in the first instance, which is used to support an audit. Finally it can be concluded that the analyzed methods offer only partial solutions for lean production optimization. There is no single approach that supports automated assessment and display of proposals for improvement.

Methodology and Overall Concept

Based on the findings of the review of existing concepts, a new method has to be developed so that a continuously consistent and operationalized evaluation of lean production systems can be guaranteed that involves all levels of lean production and automates the output of recommendations for improvement.[1]

As mentioned above, the optimization system has to assist in identifying company-specific improvement measures. So, it is in the first instance necessary to map the current state of the production system and then to evaluate it by identifying weaknesses so as to propose concrete measures.

For this, the well-known procedure of mapping the current state, identifying weaknesses, and mapping the future state has to be detailed for the purpose of this paper. As shown in Figure 1, the mapping of the current state is a diagnosis encompassing both basic and main analysis. The former addresses the identification of company characteristics with production-related data. The latter focuses on lean methods by identifying them and evaluating their effectiveness and efficiency within the network of all lean methods. The future state is actually a therapy by displaying a report of existing weaknesses and optimization measures based on both company characteristics and methods in order to provide company-specific measures. On the one hand, the optimization measures derived from the ideal situation will be correlated with the company specifics given in the mapping of the current state. On the other hand, the measures will be associated with the method characteristics.

[1] For a more detailed discussion refer to Uygun et al. (2011) and Uygun (2013)

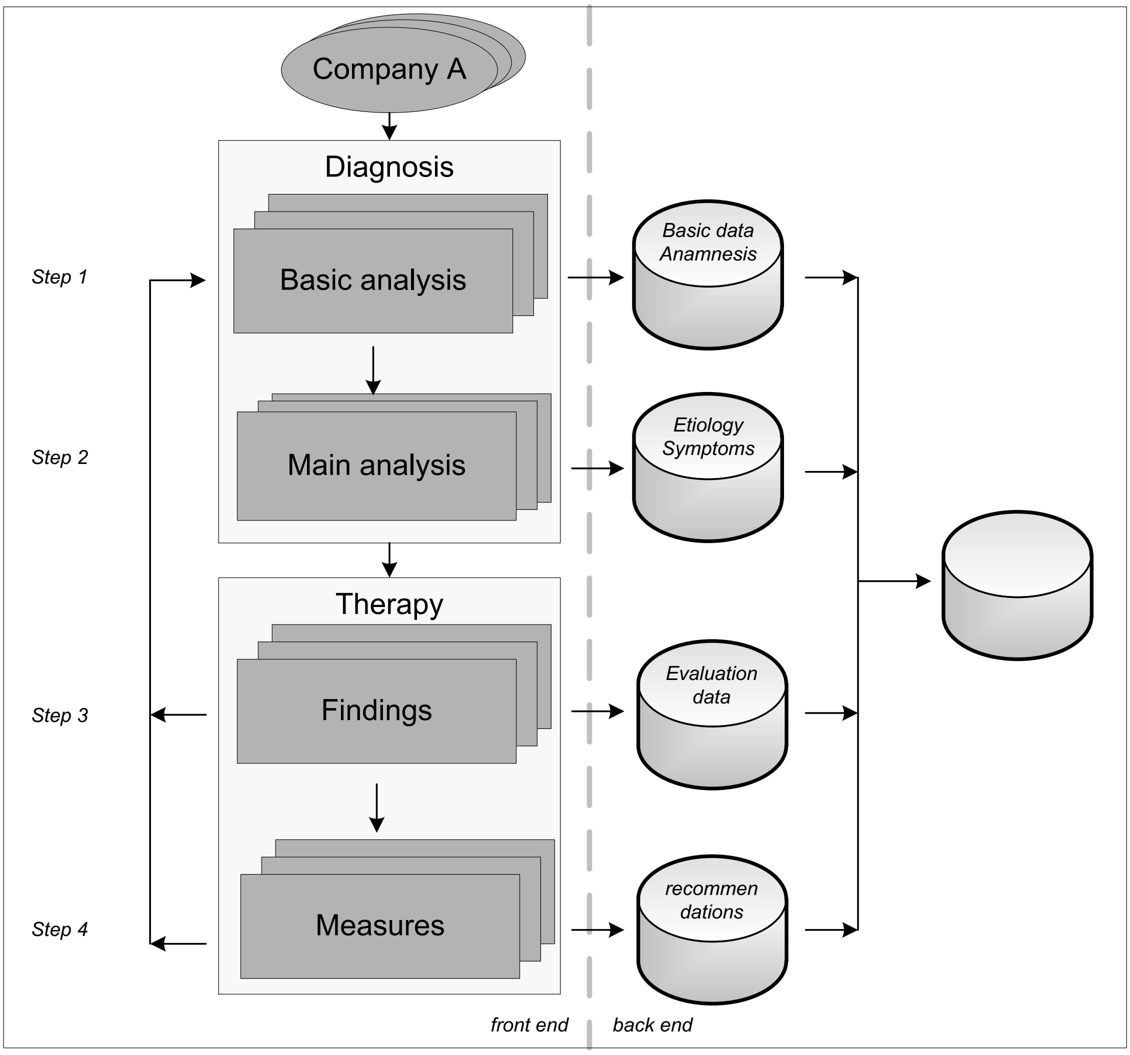

Figure 1. Overall methodology for the development of the optimization system

The optimization system has to enable the realization of these steps, as shown in Figure 1. For mapping of the current state, data have to be collected. This will be done with a questionnaire consisting of questions which have to be derived systematically and which answer choices have to be assigned to. According to this, all production-related and methods-related information have to be identified and answer choices have to be assigned to them. The answers then have to be set in correlation with each other and with company characteristics in order to give automated improvement suggestions.

Diagnosis

Basic Analysis

In the first stage, the production-relevant company data have to be collected. This step represents a basic investigation, in which the anamnesis is carried out in order to provide information about the history and circumstances of the company. With regard to the diagnosis the interdependencies of this information with the methods play a crucial role. Therefore, in addition to the elaboration of the basic data that of interdependencies also has to be carried out. Here, the influence of each individual basic data on individual methods is determined. It is analyzed in detail whether the individual basic data affects the particular method negatively or positively. The negative influence in this context can mean either that in the presence of this basic data the specific method is not applicable or this basic data has to be adapted if the method should still remain in use. The positive effect indicates that the basic conditions for the use of the specific method are given. This provision is for the evaluation of great importance. Methods that are inadequate in use, but where a positive effect by the basic data is given, should be optimized.

To record the basic data a structured derivation of lean-related data is required. Considering relevant production data, a process-oriented approach is expedient. Based on the process parameters control, content, resources, and structures, various production-related features can be grouped together. The coding of these data takes place systematically, with 0 and 3 for decision and with 1, 2, or 3 for evaluation. The expression of evaluation answers is dependent on the corresponding basic data and may be different, e.g. low (“1”) to high (“3”) or bad (“1”) to good (“3”).

Main Analysis

Lean Methods

For the main analysis, firstly, the structure of the lean reference model with type and number of elements has to be determined. To this end, relevant collections of lean methods in literature have been considered. For this, a double-track approach by considering published lean methods of both industrial companies and scientists is practical. There are numerous published production systems of companies with collections of lean methods available, like Ford, Mercedes-Benz, Audi, VW, and of course Toyota. These production systems differ either significantly or marginally. Since a lean production system is an interdependent network of methods and tools specific company suitable combination of methods must be found in the implementation and operation of lean production systems which lead to different company-specific lean production systems. This means that the selected company-specific methods must be checked for their mutual influence, whether other individual methods are required or supported (Takeda, 2006).

As to general collections of lean methods, several publications and lean method collections were considered, like Jones et al. (1999), Sullivan et al. (2002), Shah and Ward (2003), Bicheno (2004), Kumar et al. (2006), Liker and Meier (2006), and Towill (2007). Examining these collections, a high number of production organization methods become obvious. So, the major challenge is to sum up the high number of methods to a manageable quantity and to guarantee simultaneously an extensive analysis. For this purpose, these existing collections of lean methods were listed, compared, and common methods were identified and re-named. In the end, 15 so-called basic lean methods[2]

[2] for a detailed discussion of some of these lean methods refer to Uygun et al. (2015)

were derived, as listed in Table 1, which then were checked against the existing company-specific production systems so as to check their validity.

from \ to		M01 Standardized work processes	M02 Standardized Resources	M03 Quick set up	M04 Intelligent automation	M05 Small lot sizes	M06 Visualization	M07 Productive maintenance	M08 Systematic problem solving	M09 Work load leveling	M10 Pull production	M11 Just-in-time production	M12 Instant quality control	M13 Flexible employee deployment	M14 Waste-free production	M15 Continuous value adding	# active	# passive	ranking (active)	ranking (passive)	prerequisite of following methods	ranking randomly	**final rank**
Standardized work processes	M01			x			x	x	x		x	x	x	x	x	x	10	1	1	2			**1**
Standardized Resources	M02	x		x	x					x	x	x	x	x	x		9	0	2	1			**2**
Quick set up	M03					x		x		x	x	x			x	x	7	2	3	6			**3**
Intelligent automation	M04						x						x		x	x	4	1	4	2		1	**4**
Small lot sizes	M05									x	x	x	x				4	1	4	2		2	**5**
Visualization	M06									x			x	x	x		4	2	4	6			**6**
Productive maintenance	M07									x	x				x	x	4	3	4	8			**7**
Systematic problem solving	M08							x					x				2	1	8	2			**8**
Work load leveling	M09										x	x					2	6	8	10	1		**9**
Pull production	M10											x			x		2	6	8	10	2		**10**
Just-in-time production	M11														x	x	2	6	8	10		1	**11**
Instant quality control	M12														x	x	2	6	8	10		2	**12**
Flexible employee deployment	M13									x							1	3	13	8			**13**
Waste-free production	M14															x	1	9	13	15			**14**
Continuous value adding	M15																0	7	15	14			**15**

Table 1. Determining the order of lean methods

After identifying the lean methods, a sequence has to be determined so as to have a procedure for the diagnosis. In determining the order of the methods several consecutive criteria will be applied. The first criterion is the number of active influence. The method that affects most other methods, receives the highest rank. Here, however, several methods can have the same number of active influence, such as the methods M04 – M07 (see Table 1). For such cases, the second criterion comes into force. The method that is less influenced by others, receives the higher rank. The idea behind this criterion is the assumption that the method that is affected by many other methods has to be placed further downstream, whereby the influence of the preceding methods on this particular method remains. If there is still parity after this criterion, e.g. between method M04 and M05, the third criterion comes to action. Here, an analysis of the prerequisite of methods is carried out whether the equal methods require each other. This is the case with methods M09 and M10. But this is not the case with the other methods, M04 and M05 as well as M11 and M12, so that the last criterion applies. The sequence is then left to chance.

Evaluation Scheme

Subsequently, as the second stage, the main study will be conducted. This includes the systematic study of the symptoms and causes of the (wrong or suboptimal) application of the methods. It is a combined symptom-based and etiological approach. So, for each method symptoms, causes, and problems are elicited, which then palliative, cause solving, and problem solving measures are assigned to. In this context, the interdependencies between these measures have to be taken into account, especially as certain measures can support, limit, or exclude each other. So, each method is placed in a larger context of a main problem, cause, effect, and requirement. The focus is on the main production organization problem with its optimization as the main requirement which can be satisfied by means of a specific lean method. The main problem has a root cause, which in turn has a main symptom. For the diagnosis a stepwise execution of these related aspects is relevant. It should be noted that due to the overall complexity of control in this context, only the main aspect of each element is considered. A particular problem may have several causes, and these in turn may show several symptoms.

However, the main aspect is found to be sufficient for the diagnosis, which offers the greatest leverage.

Table 2 summarizes the assignment of the main problems, main causes, and main symptoms for each lean method. For example, the method M01 standardized work processes has the main problem of varying work processes that leads to variations in output results. The main reason or cause is the lack of workflow standards. This is reflected in the main symptom of increased workload.

Lean Method	Main problem	Main cause	Main symptom
standardized work processes	varying work processes	lack of workflow standards	increased workload
standardized Resources	fluctuating resource efforts	heterogeneous systems for resources	increased use of resources
quick set up	inefficient setup procedures	bad organisation of set up	increased set-up time
intelligent automation	high rejection rate and error in equipment	no continuous error control of resources	errors and defects
small lot sizes	high WIP	large lots	increased storage requirements
visualization	late intervention	unknown production conditions	deviations with delay
productive maintenance	frequent equipment downtime	equipment failure	lost time
systematic problem solving	recurrence of problems	lack of problem solving process	Problems and failures in process
work load leveling	irregularly occurring production orders	fluctuations in order load	capacity fluctuations of resources
pull production	high control effort	centralized control	increased use of resources for control efforts
just-in-time production	stock fluctuations	lack of co-production quantities with network partners	high stocks
instant quality control	resource-based deviations from quality specifications	misadjustment of resources	Variations in quality of the product
flexible employee deployment	fluctuations in employment	order load fluctuations	uneven employee deployment
waste-free production	congested material movement	inefficient planning of material flow	increased material flow cost
continuous value adding	low value-adding	high proportion of non-value adding processes	waste of all kinds

Table 2. Specific main problem, causes, and symptoms of the lean methods

Based on these information a general design method for combining the detailed problems with the specific measures is needed. For this purpose, the Axiomatic Design is expedient which is a design methodology aiming at providing a theoretical basis built on a logical and rational thought process for the design of complex systems. In addition, increased creativity of the designers, reduction of the share of random search process for a solution, minimization of iterative trials, and the transfer to the computer is addressed. This is done through functional requirements (FR) which design parameters (DP) are assigned to. Here, the term axiom is understood as a fundamental truth, functional requirements as a minimal set of independent requirements to cover all functional needs of the object to be designed, and design parameters as physical key variables to fulfill functional requirements. The Axiomatic Design is a decomposition approach, starting with a FR which one unique DP is assigned to. In the next decomposition layer FR derived from the previous DP are identified, which unique DP are assigned to. This decomposition continues till FR-DP combinations are found which cannot be further decomposed. (Suh, 2001)

The structure of the examination and diagnosis follows this Axiomatic Design principle. It has three decomposition layers, which are linked to the scope of decision and the target group (see Figure 2). In the highest layer the main requirement stands on top as the top functional requirement with the associated lean method as design parameter. The consideration of the main requirement and the introduction of its design parameter are strategic in nature and relate therefore to top management regarding lean management responsibility. Depending on size and structure of the company, this can be either lean managers or production managers. In the middle layer subsequently palliative, awareness building, cause solving, and problem solving measures are available as functional requirements associated with their design parameters. The consideration of these functional requirements of the second layer is tactical in nature and refers to middle management regarding lean responsibility. Depending on company this can be Hanchos or foremen. In the lowest layer, specific functional requirements are summarized addressing operational staff in the first place. Figure 2 summarizes these relationships.

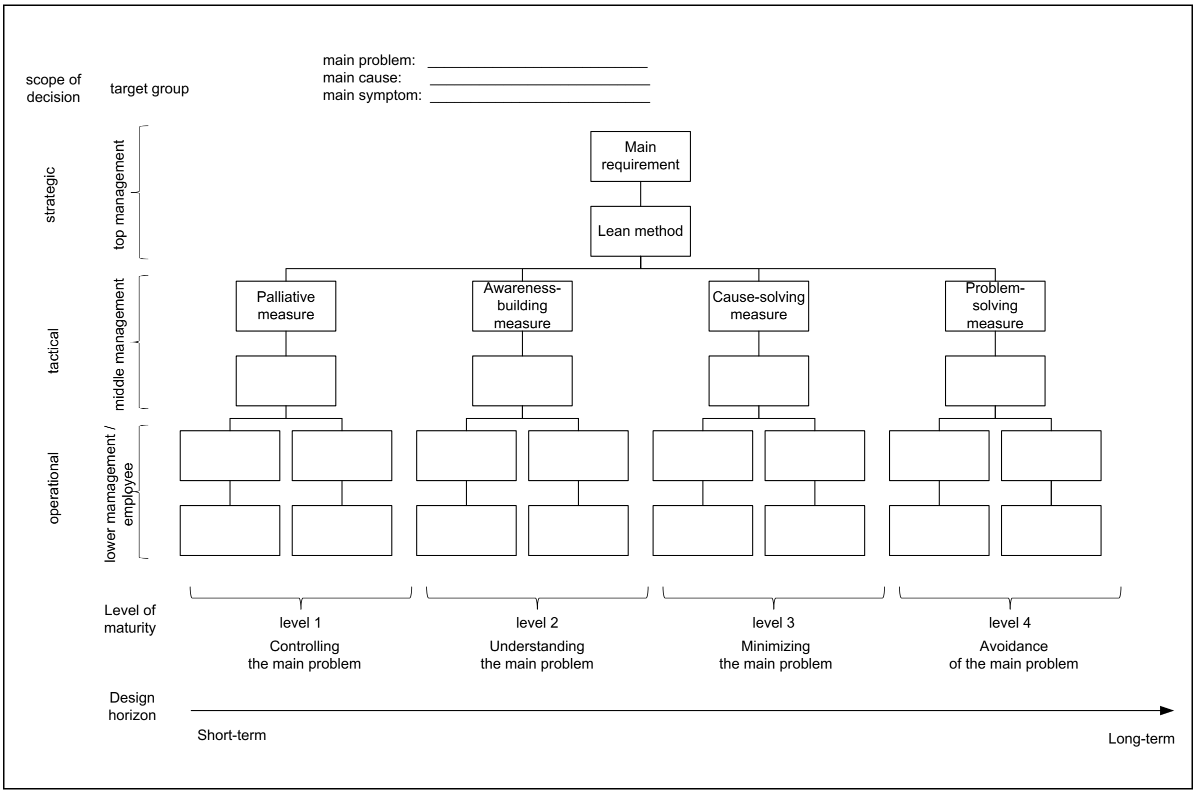

Figure 2. Structure of the diagnosis

The diagnosis provides four maturity levels. The remedy of the main symptom can be realized by palliative or symptom-relieving measures. Through this, the main problem is merely controlled without making any structural changes. This is also the lowest level of maturity. To achieve the next higher level of maturity, awareness has to be achieved for the main problem and the lean method. Here, the fundamentals of the lean method are conveyed, which is used to fulfill the main requirement that is derived from the main problem. The third level aims at minimization of the main problem. To remedy the main cause, a cause-solving measure is proposed. The solving of the main problem is possible with a problem-solving measure that can prevent the cause. This represents the highest level of maturity.

Furthermore, the design horizon is linked closely to the maturity levels. The first maturity level measures are rather short-term ones, which can be implemented within a few days, whereas the fourth level measures are likely to be long-term.

Based on this structure the particular questions are derived. The functional requirements are formulated as questions and are made available to the relevant target groups. The design parameters are the appropriate responses or actions. The questions will be provided with standardized answers. Important in this context is the coding of the questions and answers. A four-digit code is used, which for example could be M0133. The "M" indicates that the code refers to the method, in contrast to the basic data, where a "B" is prefixed. The next two digits represent the methods that are numbered in order of sequence (see Table 1). The number 01 represents the first method standardized work processes. Depending on the layer, the following numbers are assigned either zero or more digits. The code M0100 is the question of the functional requirement of the top level. Finally, the third digit stands for the maturity level and the fourth digit for the question of the lowest layer of each maturity level. Thus, the code M0130 is the question for the third maturity level of the functional requirement of the second layer and the code M0133 for the question of the functional requirement of the third maturity level of the third layer.

The systematically derived method answers as design parameters of the corresponding functional requirement (=method question) have on the lowest layer influences on functional requirements of the same maturity level of other methods. Based on the type of influence it has to be distinguished that the answers and design parameters of the first maturity level are merely to be considered when analyzing other functional requirements of the same maturity level of the same layer. The ones of higher maturity levels actively support other functional requirements of the same maturity level on the same layer. Thus, influencing design parameters of functional requirements of other methods of the lowest maturity level will simply be listed without a call for implementation. This is due to the fact that the first level is a mere mapping of the current state with widely used emergency measures in industry which have to be replaced by measures of higher levels. The listing of such design parameters gives a first indication of the interdependence of even such emergency measures. In the output of the results of the higher levels, however, the design parameters of the functional requirements of other methods are mentioned as supportive measures for the considered method to be taken into account in the implementation of the design parameter of this considered method in order to exploit the full potential of the functional requirement. The comprehensive analysis of influence of all design parameters on other functional requirements is done for all basic lean methods.

The functional requirements will be displayed as questions. These can be open, closed or semi-closed. Open questions give no answers, whereas semi-closed questions specify several finite answers. Finally, closed questions include answers which can refer to decision, evaluation, or trend. For the latter a three-step scale has been used which is ordinally scaled (e.g. from unsystematic to systematic). For the diagnosis open questions are omitted, and semi-closed and closed questions will be asked. For a standardized evaluation certain categories of response with well-defined response alternatives are used, e.g. systematic, regular, or frequent. All questions can be answered with at least one answer in each category. The coding of the answer default is done with the values 1, 2, and 3, respectively from negative to positive. For example, the answer defaults of the answer category “systematic” are coded with a "1" for "unsystematic" and with a "3" for "systematic". These values are of fundamental importance for the evaluation.

For questions with more than one response category a cumulative coding of answers is necessary, which will be used in the evaluation of the correlation with basic data as well as with other methods. Generally, the cumulative value of answers range between n and 3n, where n is the number of different response categories. So, for each number of different response categories cumulative intermediate values are developed.

The answering and output of results is available target-group dependent. Here, an upward integration is carried out, i.e. that only the higher layers have access to deeper layers. The top management has access to all evaluation data, whereas the middle management can only look into data of the operational staff. The operational staff has only access to its data analysis.

Therapy

In the third stage, the evaluation of the previous analysis is done. The findings are displayed that reflect the actual state on the basis of the answered questions. For this, all answers have to be given structured and clearly, so that individual deviations from the ideal or problems can quickly be detected. After completing the diagnostic questions, the results for therapy can be seen. It consists of two components, the findings and suggestions for improvement (see Figure 3).

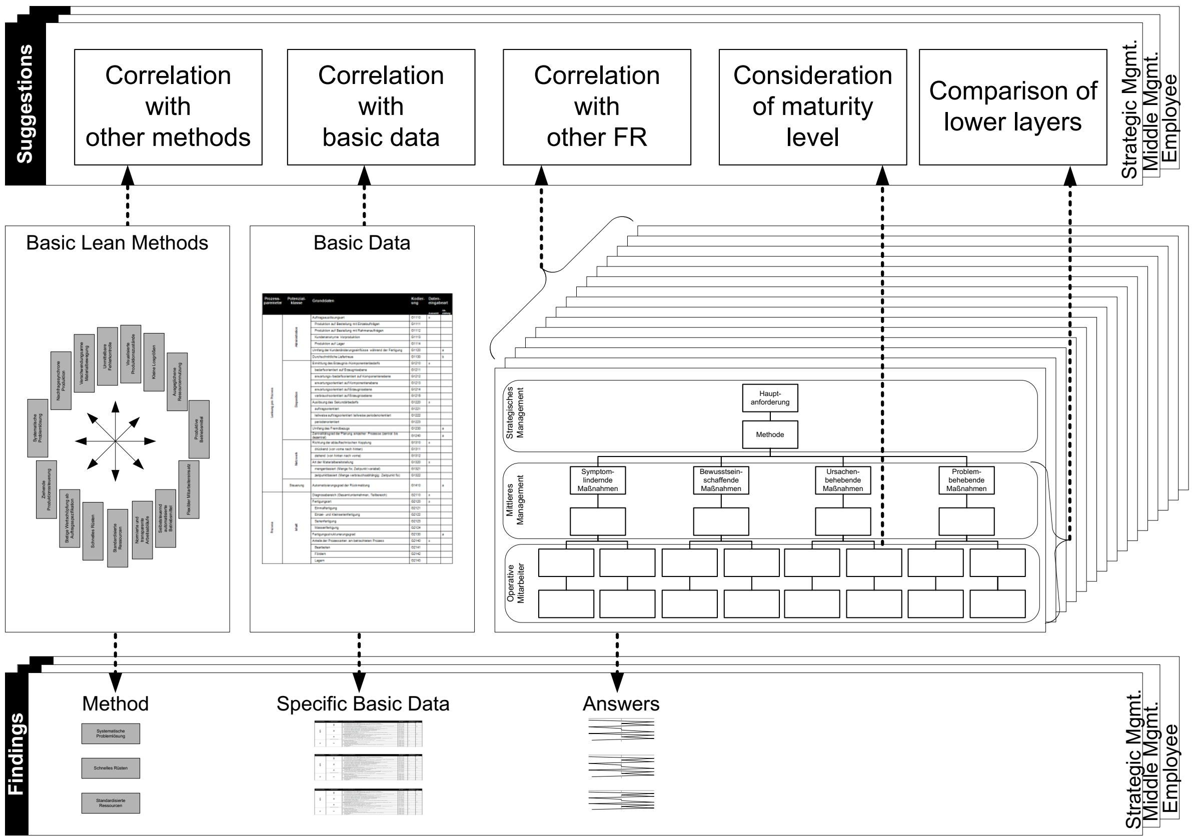

Figure 3. Overall concept of the results

The starting point of the results is the output of the method-specific findings and the current state with the collection of all answers to basic data and methods. Based on the findings for each method, improvement proposals regarding effectiveness and efficiency are then made, which are related to the identified problems. Regarding effectiveness, problems are correlated with basic data and other methods, whereas the correlation of answers of questions of other methods (functional requirement), maturity levels, and layers address the efficiency.

Measures for Effectiveness

As a first step, suggestions for improvement are issued relating to the correlation between the answers to the functional requirements with the basic data. The captured basic production-related data influence the adoption and use of certain lean methods. The presence of certain basic data may limit or favor the introduction of a lean method.

In the case of limitation, improvement suggestion can be either the removal of the lean method or the adaptation of the corresponding basic data, if the lean method shall still remain in use. In the case of favoring, the use or application of the lean method is strongly recommended.

Regarding the correlation with other methods the urgency of the implementation of the regarded method is given. If a method is declared out of deployment by the top manager, the implementation of this method is demanded with a specific intensity depending on its interdependencies with other methods. The correlation with other methods results in the Response Spectrum I which indicates the intensity based on the number of supporting methods. Based on this correlation, the urgency of the implementation of the method can be derived.

Measures for Efficiency

In addition to the measures concerning effectiveness, there are also measures addressing the efficiency of the deployment of lean methods. The correlation of the basic data with the answers to the questions of the methods (or functional requirements) is the first one dealing with efficiency. In this context, the measures are also marked with an urgency. For this the Response Spectrum II as a 3x3 matrix is spanned, which sets the evaluation of the basic data ("1" to "3") in relation with the answer of the question of the considered method ("1" to "3"). Based on this correlation, the urgency of the implementation of the measure or design parameters associated with this question can be derived. It should be noted that for methods which more than one basic data have influence on, a basic data value is to be determined. In the evaluation, the highest value is taken as a basis from the amount of checked basic data. For example, if all basic data are evaluated with "1" except one with "3", the maximum value ("3") is taken as the basic data value. In the recommendation, the urgency is then justified by the existence of this basic data. For example several basic data, like type of order generation, level of customer change requests, production type, etc., have influence on method M03 (quick set-up). If only one of these basic data is checked with "3" and the rest with "1", and for example, the question of the considered method (functional requirement) M0332 has after the accumulation the value "1", the implementation of the corresponding design parameter will be recommended with the highest urgency. However, if none of the basic data are higher than 1 and the question of the FR of the considered method has after accumulation the value "3", the improvement measure is recommended with the weakest intensity.

As mentioned above, the questions have been derived systematically using Axiomatic Design which have been independently decomposed at all levels. However, some design parameters of a functional requirement on a maturity level affect functional requirements of another method on the same maturity level, so that a "decoupled design" is given which is a yet acceptable solution. These interrelationships are also of high importance. In the generation of improvement measures (=design parameters) for a method, such as M02 (standardized resources), the influence of upstream design parameters of functional requirements of other methods on the same maturity level are considered. For this, a complete and detailed list of all influences is generated. The urgency of improving the considered method is also of relevance. Depending on the evaluation of interacting FR-DP combinations an urgency to implement the design parameters is set. This correlation is standardized systematically with the Response Spectrum III as a 3x3 matrix spanned by the evaluation value of the influencing upstream FR ("1" to "3") and the evaluation of the considered FR ("1" to "3").

Furthermore, the consideration of the maturity level is of interest. The diagnosis is based on four levels of maturity (see Figure 2). Their individual achievement is tracked successively. If a functional requirement of the second maturity level, which is answered by the middle management, is poorly met (=”1” as cumulative intermediate value after accumulation of all answer values according to the calculation scheme similar to that for basic data), the next maturity level will not be displayed to employees.

Concerning the comparison of lower layers, the middle management and operational employees answer the same questions. Therefore, a comparison of the responses of these two layers can be realized by comparing each answer values of both.

Technical Realization

The developed concept was programed in a further step. For the development of the evaluation system certain technologies were used on both server and client. On the server side PHP (Hypertext Preprocessor) and MySQL (Structured Query Language) were used. The former includes PDO (PHP Data Objects), which is a database access layer and a uniform method of accessing PHP on different and multiple SQL-based databases, such as MySQL. On the client side web browsers with HTML (Hypertext Markup Language) and JavaScript are used. The latter also includes jQuery, jQueryUI, AJAX (Asynchronous JavaScript and XML) and JavaScript Object Notation. The former is a fast and accurate JavaScript class library for document object model manipulation, plug-ins and Ajax functionality. The jQueryUI uses this and is used to design user interfaces (UI) with advanced effects and animations.

The coding was carried out using a central database. There are twelve tables available, which can be roughly divided into the three different tasks of administration, questionnaires, and persistence. Administrative tasks include the tables "user", "process", "department" and "company". The table "company" consists of departments, which in turn are divided into processes. Users belong to departments and can provide answers to all the processes of their department according to their rank.

The questionnaire tasks relate to the generation and evaluation of questionnaires with tables containing functional requirements, basic data, design parameters, interdependencies of basic data with functional requirements, interdependencies of methods among each other, and methods. There are different questionnaires for each process. From the table of the basic data the basic data questionnaire for every process is generated. Furthermore, for each process, the questionnaires for the methods are derived from the table containing the functional requirements. For generating measures, the given answers are correlated with the respective tables containing interdependencies of basic data with functional requirements, interdependencies of methods among each other, and methods, with basic data, other design parameters, and other methods.

The tasks of persistence of user responses include the tables for answers to functional requirements of methods and basic data. The table containing answers to basic data embraces basic data about each process. The table for answers to functional requirements contains all answers of questionnaires of the methods.

Case Study

The optimization system was validated with a tier-1 automotive supplier that produces hydraulic and vacuum pumps for several car manufacturers. The scope of the diagnosis covered the production line of the pumps with the plant manager for the top management layer, the production manager for the middle management layer, and seven employees for the lowest layer. Firstly, the plant manager answered the functional requirements of the upper layer resulting in the announcement of the deployment of seven lean methods, which are M02, M05, M10, M11, M13, M14, and M15. Successively, the production manager and all seven employees one after another answered the questions to the functional requirements. According to the responses, the corresponding design parameters with their specific intensity were given as improvement measures.

As general findings, following weaknesses were witnessed thanks to the optimization system. The interpretation of them is based on feedback meetings in a big round and on an individual basis. As to correlation with basic data, there is hardly employee awareness for both the individual methods and the lean production system as a whole. Only theoretical inputs were given without having any training off and on the job. This is caused by the hastily implementation of the lean methods due to the pressure of the automobile OEMs to implement the methods they also have. This led to the non-reflected implementation of the abovementioned methods without considering the interdependencies. So, it was not surprising that some supporting methods were missing. In addition to that, considering the correlation with other design parameters, a lack of significant number of supporting upstream design parameters occurs. With regard to the maturity level, there is only the second maturity level reached at most of the methods. The most striking finding is the deviation in the answers of the production manager and the employees. In general, all seven employees evaluated the functional requirements worse than the production manager. The main reason for this perception is the displeasure of the employees to be forced to work with these methods without having the opportunity to give feedback.

Conclusion

The developed evaluation system consists of two components, the diagnosis and the therapy each of which consist of two steps. The former captures the basic and main analysis. Within the basic analysis production-relevant company data are registered. Secondly, the main analysis takes place, in which the symptoms and causes of the inadequate application of the methods are systematically studied. Within the therapy findings and measures are suggested. The findings represent the current state. The most important part is the measures. Here, measures are given through correlation with basic data, other methods, design parameters of other methods, maturity levels and layers are issued on the basis of coordinated measures that are related to the identified problems.

The developed diagnostic system thus supports the user in the context of the continuous improvement process that involves key persons in relation to the development of lean production systems. Thanks to the database structure, all data will be saved with a time stamp so that the development of the improvement of the lean production system can be tracked.

The case study showed the importance of the consideration of the interdependencies and the integration of employees which have to deal daily with these methods.

So, summing up, it can be stated that the here developed evaluation system for goods-producing companies is based on a comprehensive data recording showing weaknesses in the application of lean production systems and suggesting specific measures that are coordinated. Therefore the evaluation system takes into consideration the multiple connections within a lean production system which was so far lacking.

Further research will be conducted applying the evaluation system in more and diverse companies in order to examine typical industry or company-specific problems.

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