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How can we do our best, in manufacturing processes?

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Abstract. The paper presents synthetically the main methodologies for production systems optimization. There are presented: Six Sigma, Theory of Constraints, Toyota Production System, Lean Manufacturing, Agile Manufacturing and Smart manufacturing. The comparative study analyzes the goal, the main focus, the observed problems, the methodology, the desired outcome, the primary, but also the secondary effects and some critics for each methodology. Based on such an analysis, managers can choose the optimization methodology that best suits the organization's strategic goals, technological level, and organizational culture.

1. Introduction

We live in an increasingly dynamic world, characterized by global competition and unprecedented scientific, technological and informational development. The products are becoming more sophisticated, their life cycles are getting smaller and consumers are becoming more and more demanding. In this context, companies are subject to increasing external pressures. They can remain on the market only by developing new, more competitive products, by gaining new markets, expanding, designing new technologies and optimizing the existing ones.

The benefit of the companies can be achieved by launching new, more attractive products in accordance with the specific requirements of the customers and sold them at a competitive cost, but also by lowering the production costs.

Lowering production costs can only be achieved by optimizing the production systems. Several methodologies were designed to optimize production. The classic ones are Six Sigma, Theory of Constraint and Toyota Production System. The Toyota manufacturing system has been implemented, adapted and developed in the Western world as the Lean Manufacturing methodology and later in Agile Manufacturing. Now days, the Smart Manufacturing concept has been developed, which is consistent with Industry 4.0.

The paper aims to present these production optimization systems and to highlight some of their characteristics, but also to analyse them comparatively, underlining the type of organization and culture in which it is useful to implement each of them.

2. Production optimization methodologies

2.1. Six Sigma

Six Sigma is seen as a set of statistical tools, an operational philosophy of management, a business culture, but is generally regarded as a well-structured continuous improvement methodology to reduce process variability and remove waste within business processes [1].

Six Sigma can be implemented through two methodologies: DMAIC (Design, Measure, Analyse, Improve, Control) and DFSS (Design for Six Sigma). DMAIC is generally used for process improvement, in companies with stagnant market or relatively less competition, when focusing on cost reduction and DFSS in companies with strong market growth and competitive position, for new development of product and services, used in the context of new product development that focuses on quality from the very beginning [1]. Literature presents many variations of both.

The basic DMAIC tools include flowcharts, check sheets, Pareto diagrams, cause/effect diagrams, scatter diagrams, histograms (corresponding to Yellow-Belt level of competence) and more advanced statistical tools for process control as regression analysis (with indicator variables, curvilinear regression and logistic regression), hypothesis testing, control charts and Design of Experiments (corresponding to Black-Belt level). DFSS supplementary includes innovation tools such as the theory of creative problem solving and axiomatic design [2].

There are many benefits that can be derived from the adoption of Six Sigma. The most frequently cited are the reduction and prevention of defects which affect the quality of both products and processes. Six Sigma is used to find and eliminate the root causes of the problem and to reduce the variability in the process, in order to prevent defects. It can improve product development cycles and process design and also can short product lead times by reducing the cycle time of the overall manufacturing process.

2.2. Theory of Constraints

The Theory of Constraints (TOC) is focused on making profit – both in the short term and in the long term [3]. It is a methodology for identifying the most important limiting factor (the constraint) that stands at one moment, in the way of achieving the organization goal. Then, it offers a methodology for constraint improving, until it is no longer the limiting factor [4].

The methodology consists in a set of tools [5]:

- Throughput Accounting (a method for measuring performance and guiding management decisions);
- The Five Focusing Steps (a methodology for identifying and eliminating constraints);
- The Thinking Processes (tools for analysing and resolving problems).

Because TOC is focused on making money, any analysis starts with the accounting analysis. Four key parameters are measured: Net Profit, Return on Investment, Productivity, and Investment Turns.

$$\text{Net Profit} = \text{Throughput} - \text{Operating Expenses}$$
$$\text{Return on Investment} = \text{Net Profit} / \text{Investment}$$
$$\text{Productivity} = \text{Throughput} / \text{Operating Expenses}$$
$$\text{Investment Turns} = \text{Throughput} / \text{Investment}$$

The optimization functions are focused on (in order of priority): Throughput maximisation, Investment minimisation and Operating Expenses minimisation. The maximum focus is on Throughput maximisation (increasing sales) and less on cutting expenses (Investment and Operating Expenses). After this analysis, it’s important to find the biggest constraint, which includes the symptom and the real problems).

For solving the constraint, a method consisting on Five Focusing Steps is proposed:

- Identify the current constraint - a single part of the process limits the rate at which the goal is achieved);

- Exploit - Make quick improvements to increase the throughput of the constraint using existing resources (make the most with your available resources);
- Subordinate - Review all other activities in the process to ensure that they are aligned with and truly support the needs of the constraint;
- Elevate - If the constraint still exists, further actions can be taken to eliminate the problem from being the constraint. In some cases, capital investment may be required;
- Repeat - The Five Focusing Steps opens a continuous improvement cycle.

A Thinking Processes is proposed to be used on each decisional step. This process is based on the answers to the following three questions: What needs to be changed? What should it be changed to? What actions will cause the change?
The method can be applied in all the subsystems of an organization and not just in the production system.

2.3. Toyota production system

Toyota production system (TPS) is an integrated socio-technical system, developed by Toyota. Its aim is production cost cutting through removal of waste.
Fourteen principles underlying the TPS are organized in four sections [6]:

- Long-Term Philosophy;
- The Right Process Will Produce the Right Results;
- Add Value to the Organization by Developing Your People;
- Continuously Solving Root Problems Drives Organizational Learning.

Toyota has developed two very important production strategies: Just-in-time production and Jidoka. The Just-in-time production is a method to which the production lead time is considerable shortened by producing the necessary parts at the necessary time and having on hand only the minimum stock necessary to hold the processes together".

The term Jidoka means to stop the equipment or operation, whenever an abnormal or defective condition arises.

This production optimisation method was developed in the specific Japanese culture which has some characteristics different from that held by the European and American workers.

The Japanese features include: group consciousness, sense of equality, desire to improve, and diligence born from a long history of' a homogeneous race, high degree of ability resulting from higher education brought by desire to improve, centring their daily living around work [7].

2.4. Lean manufacturing

Lean manufacturing includes the principles of Toyota Production System. The concept was presented in the international best-selling book “The Machine That Changed the World” by James P. Womack, Daniel Jones, and Daniel Roos [8]. Womack and Jones provided five lean principles: value, the value stream, flow, pull, and perfection, described in the following way:

- Value is defined by the ultimate customer;
- The value stream is the set of all the specific activities required to bring a specific product through the internal value chain;
- Flow is about making the value-creating steps flow;
- Pull refers to using a pull schedule; and
- Perfection is concerned with making improvement a continuous effort.

Additionally, besides Toyota's reducing waste purpose, Lean manufacturing explicitly declares its following goals [9]:

- In order to remain competitive on the market, a company must understand its customers’ needs and design products and processes to meet their expectations and requirements;
- Reducing lead time is a very effective way to eliminate waste;
- Reducing total costs can be achieved by producing only to customer demand.

Lean is seen by many authors as a generalization of the Toyota Production System into other culture (the American and occidental one) and industries. There are some elements over which Lean Manufacturing has a higher focus (than TPS) [9].

- Focus on maximizing profit by reducing production costs. "Value curve analysis" promises to directly tie lean improvements to bottom-line performance measurements.
- The development of new tools for improving production activity and a higher focus on those tools developed by Toyota. To assess the state of the system under review, value stream mapping and a series of key performance indicators (KPIs) have been developed. More attention is paid to work standardization. However, the instruments have their limits and only one instrument cannot solve the problems themselves.
- "Change agents" have been trained in the Toyota system to push improvements in the production system. In Lean Manufacturing the emphasis is on developing the specialist, while the supervisor skill level is expected to somehow develop over time on his own.
- The Lean concept has become a cult in the West, in many situations; a greater importance is given for tools than for solving the problems.

Some specialists consider that TPS is more pragmatic and better responds to the needs of actual businesses, while some Lean parameters (Maximise Customer Value, Perfect Processes, Perfect Value), does not reflect the real needs of an actual business. The analysis of companies that have successfully implemented Lean Manufacturing showed that [10]:

- Successful lean plants are characterized by a specific organizational culture. They show a higher institutional collectivism, future orientation, a humane orientation, and a lower level of assertiveness.
- Hard lean practices (lean technical and analytical tools) are order-qualifier activities for lean plants.
- Soft lean practices should be considered as strategic order-winner factors. Examples are: small group problem solving, employees' training workers to perform multiple tasks, supplier partnerships, customer involvement, and continuous improvement.
- Greater use of soft (rather than hard) Lean Manufacturing practices differentiates successful lean plants.

This results show that the TPS focus on humans is important and successful even when Lean Manufacturing System is implemented.

2.5. Agile Manufacturing

Global competition, new technology, customized solutions and new product introduction are the forces that drive companies to become more and more dynamic and competitive. In this context, after 2000, Agile Manufacturing emerged as a new concept of company optimization, concept which starts from and completes Lean Manufacturing.

Agile manufacturers place equal importance on both cost and responsiveness, being focused on quickly respond to the changing requirements of the customers [11].

Agile Manufacturing is characterized by customer-supplier integrated processes for product design, manufacturing, marketing, and support services. It requires enriching of the customer; cooperating with competitors; organizing to manage change, uncertainty and complexity; mobilizing people and information [12].

The latest researches [13] focused on the systemic analysis of the external environment of companies and on the major role of the big data. A framework of the expected relationship between market turbulence, enablers of agile manufacturing, competitive objectives and performance outcomes gives a new, more complete meaning to this type of manufacturing.

- Actual Big data and Business analytics, is capable to offer huge information. The variety and volume of big data, processed and interpreted through business analytics (regression modelling, decision trees, Bayesian statistics, neural networks, Support Vector Machine, and nearest

neighbour algorithms, statistics to forecast future events based on what has occurred in the past) have a high predictive power.

- Some authors consider that the enablers of agile manufacturing are: organisation, people, technology and planning [14]. Other authors found six big areas: technologies, employee empowerment, customer focus, supplier relationships, a flexible manufacturing system and organizational culture [15]. The enablers of agile manufacturing are supported by application of the most advanced manufacturing concepts and technologies, such as Computer-Integrated Manufacturing/Services, Manufacturing/Service Strategy, Enterprise Integration, Rapid Prototyping, New Product Development, CAD/CAM, Simulation, Multimedia and MRP II Business Process Reengineering, Systems Design and Operations and Supply Chain Management, Enterprise Resource Planning, SAP, E-Commerce etc.
- Competitive objectives consist of the set of values delivered to customers, which are: low-cost, quality, speed, dependability, product customization, volume flexibility and leadership in new technology products.
- Performance indicators allow the measuring of the business success – both financial and non-financial. The most popular financial measures are sales turnover, net profit, market share, proportion of sales turnover from new products, customer loyalty based on repeat orders and performance relative to competitors. The measuring of the non-financial indicators represents a big provocation for every company.

Many authors try to develop technological models for these new, agile manufacturing systems.

A solution is the reconfigurable manufacturing system, which allows flexibility not only in producing a variety of parts, but also in changing the system itself. This system tends to claim six capabilities: modularity, integrability, customization, convertibility, scalability and diagnosability. Such a system will be created using basic process modules (hardware and software) that will be rearranged quickly and reliably [16].

Another solution is the Cooperative Manufacturing System, which significantly depends on the existence of a collaborative/cooperative robot (cobot). A cobot is usually a Light-Weight Robot which is capable of operating safely with the human co-worker in a shared work environment. There is a slight difference between the definition of collaboration and cooperation in robotics. In cooperative robotics, both the worker and the robot are performing tasks over the same product in the same shared workspace but not simultaneously. Collaborative robotics has a similar definition, except that the worker and the robot are performing a simultaneous task. Gathering the worker and the cobot in the same manufacturing workcell can provide an easy and cheap method to flexibly customize the production. Moreover, to adapt with the production demands in the real time of production, without the need to stop or to modify the production operations [17].

Analysing comparatively Lean Manufacturing and Agile Manufacturing, we can see that both use a number of common practices such as waste elimination, setup time reduction, continuous improvement, 5S and other quality improvement tools.

There are, however, strategic differences between the two. Lean Manufacturing is associated with resource efficiency and high performance, and agility with capabilities addressing customer requirements. A turbulent environment influences the adoption of agile manufacturing.

A complex analysis was done by Hallgren [18]. Both lean and agile manufacturing can be seen as responses to increasing competitive intensity in the industry. The analysis started from the three major routes to competitiveness: cost leadership, differentiation, and focus.

- A cost-leadership strategy means that the company strategy is to offer products that are equivalent to those offered by competitors, but more efficiently than competitors. Cost leaders would emphasize cost reduction and firms strive to reduce waste and so, to become the low-cost producer. A cost-leadership strategy is well aligned with lean manufacturing operations capabilities and cost performance.

- In a differentiation strategy, the objective is to create a product or service that is, or is perceived to be, unique by customers. To fulfil this strategy, agile manufacturing is the solution because it offers high level of flexibility, delivery speed and reliability as well as quality conformance.
- The focus strategy is targeted towards one or more market segments of the company's markets. Within a focus strategy, the firm can choose either a cost leadership or a differentiation approach.

Lean Manufacturing requires elimination of all forms of waste, including time, and it requires the implementation of a level schedule, while Agile Manufacturing requires the use of market knowledge and a virtual corporation to exploit profitable opportunities in a volatile market place [19].

2.6. Smart manufacturing

There is no generally accepted definition of Smart Manufacturing. According to the National Institute of Standards and Technology (NIST) Smart Manufacturing is a fully integrated, collaborative manufacturing system that responds in real time to meet changing demands and conditions in the factory, in the supply network and in customer needs [20].

Smart Manufacturing is an emerging form of production integrating manufacturing assets of today and tomorrow with sensors, computing platforms, communication technology, control, simulation, data intensive modelling and predictive engineering. It utilises the concepts of cyber-physical systems spearheaded by the internet of things, cloud computing, service-oriented computing, artificial intelligence and data science. Once implemented, these concepts and technologies would make Smart Manufacturing the hallmark of the next industrial revolution [20].

The main pillars of smart manufacturing are [20], [21]:

- intelligent products (Smart products are uniquely identifiable, may be located at all times and know their own production and testing history, current status and alternative requirements needed to achieve their targets);
- manufacturing technology and processes (Additive manufacturing, hybrids of traditional and additive processes, laser and net-shape manufacturing, new generation of low cost robots, new smarter manufacturing equipment equipped with sensors and software capabilities, new 'cyber' jobs rather than traditional jobs, sharing manufacturing and transportation resources across manufacturing chains etc.);
- materials (Smart materials as shape memory alloys, functionally graded materials, materials which include organic-based materials and biomaterials; The importance of recovering materials from products at the end of their lifecycle will increase);
- data (Greater collection of data from diverse sources. The data will be used to develop any application, including predictive models which allow extraction of past and new knowledge related to manufacturing. There is a great need for selecting useful KPIs for any manufacturing process. MESA Association is working with ISO on plant-level assessment standards by defining KPIs by providing commonly accepted performance measures (ISO 2011; 2014). NIST Engineering Laboratory, in a joint effort with the MESA metrics group, is developing a method and models for selecting KPIs appropriate for any manufacturing process. The standardized method should simplify the KPI selection process while maintaining the reliability and validity of measurements [22]);
- predictive engineering, (Traditionally, data was used for analysis, monitoring and control; Predictive engineering offers a new paradigm of constructing high-fidelity models with both limited-scope models (e.g. behavior of a supply chain) and those that involve multiple systems (e.g. models that integrate productivity, product quality, energy and transport) to support decisions concerning future production and market conditions);
- sustainability (The goals of sustainability efforts will be materials, manufacturing processes, energy and pollutants attributed to manufacturing.);
- resource sharing and networking (Manufacturing is becoming more digital and virtual, much of the creative and decision-making activities will take place in the digital space. Smart

manufacturing will share manufacturing equipment, software, expertise and most importantly, the collaborative modeling and creativity space. Material handling and transport of materials, components, products and people as well as the concept of vehicle connectivity will be important factors in evolving the spatial configuration of manufacturing on a regional and global scale. Application of the principles similar to those of Facebook and Wikipedia to various areas of manufacturing will be realized probably in the next decades. [20].

Decision making is extremely important in smart manufacturing. The steps of a data-driven model for the decision making process based on a generalized description of decision making was developed The steps are [23]:

- "Scope," refers to defining the boundaries and key performance indicators (KPIs) and metrics needed to address the goal of the decision;
- "Identify" determines the data and information needed to support the calculation of KPIs and metrics within the boundaries of analysis;
- "Collect" requires using tools and methods to gather the identified data and information from the system of interest;
- "Transmit" requires using tools and methods to move the collected data and information from the system of interest to where it may be analysed;
- "Analyse" is the calculation of the identified KPIs and metrics from the collected data and information using appropriate methodologies;
- "Share" refers to accessing previously generated data, knowledge, and resources to reduce the cost, expertise, time, and training needed to generate new intelligence through analysis;
- "Retrieve" is the storing and accessing of generated intelligence quickly and accurately without losing knowledge to support future decisions.

The development of a Reference Architecture is an important framework which will allow the development of Smart companies, and their reconfiguration over their lifecycle period. Several Reference Architectures were developed through time beginning with Cimosa, Pera Aris, and later Geram, Togaf etc.

In concordance with the actual needs of the Smart Manufacturing, the Reference Architectural Model Industrie 4.0, abbreviated RAMI 4.0 was developed. This model consists of a three dimensional coordinate system that describes all crucial aspects and standards of Industrie 4.0. The complex interrelations of a Smart company can be broken down into smaller and simpler clusters. It also provides a framework for understanding where current standards can be used [24].

Another Reference Architecture is the Line Information System Architecture, (LISA), an innovative, yet simple architecture and design pattern for rapid integration of smart services into existing factory infrastructure. LISA is an event- and service-based information system architecture that is used to integrate devices and services, also called the Tweeting Factory. Simple messages (tweets) from all kinds of devices are sent out and transformed into high-level knowledge that is used by smart services for online monitoring, control, optimization, and reconfiguration [21].

When speaking about optimisation in Smart Manufacturing, all the paradigms discussed before can be used. This includes Six Sigma, TOC, TPS, Lean, Agile, Sustainable, Digital, and Cloud manufacturing. Smart manufacturing can enable aspects of these paradigms for all manufacturers from small businesses to large enterprises [25].

3. Comparative analysis of the main production optimization methodologies

Each optimization starts from information that suggests that something is going wrong in the organization and an improvement should be made.

The source of the information may be different; it may come from customers, from suppliers, from competitors or from various departments of the company. Information can be narrative or more precise. The values of some financial or production parameters, or some durations can be known. Companies can have data histories for some parameters or more complex data bases.

Table 1. Comparative analysis of the main production optimization methodologies.

Method	Six Sigma	Theory of Constraint	Toyota Production System	Lean manufacturing	Agile Manufacturing	Smart Manufacturing
Goal	Achieve stable and predictable process results by reducing process variation	Make more money now and in the future	Cost reduction, Productivity improvement	Perfect value	Quickly respond to customer needs and market changes while still controlling costs and quality.	Respond in real time to changing demands and condition in the factory, in the supply network and in customer needs.
Focus	Problems	System constraint	Human	Flow	Market	All the problems faced by the organization
Observed problems	Quality problems	Net Profit, Return on Investment, Productivity, Investment Turns	7 wastes	7 wastes, Value stream map, KPIs	Customer needs in a turbulent market	KPIs benchmarks
Methodology	DMAIC (Design, Measure, Analyze, Improve, Control), DFSS (Design for Six Sigma)	Identify constraint, Exploit constraint, Subordinate process, Elevate constraint Repeat cycle	Just in time, Jidoka, Kaizen	Specify value, Identify the value stream, Flow, Pull, Perfection	Modular product design Information technology High level of planning Corporate partners Knowledge culture	The agile, reconfigurable and wireless factory, Manufacturing system architecture, Collaborative manufacturing , Big data
Desired outcome	Customer satisfaction - Survival	High plant performance	Customer satisfaction - Survival	Maximize customer value	High level of customer satisfaction	Enable rapid, agile, and cost-effective production of complex, first-to-market products
Primary effect	Uniform process output, improved quality	Fast throughput	Reduce waste	Reduce waste, Reduce lead time	Differentiated products Reduce cost	Very differentiated products, Low cost
Secondary effect	Reduce waste Fast throughput	Reduce lead time, Reduce waste, Improved quality	Improved quality, Reduce lead time, Fast throughput	Improved quality, Fast throughput	Fast throughput Improved quality,	Fast throughput Very small lead time
Criticism	Process improved independently	Autocratic culture – minimal worker input	Statistical or system analysis not valued	Statistical or system analysis not valued	High level of technology,	Very high level of technology, Integration in a reference architecture

Companies' objectives may also be very different. There are companies that have a stable market and their aim is only to reduce production costs. There are also companies that operate on a very dynamic, competitive market and have to diversify their production. There are companies with simple organizational structure, others supported by sophisticated computer systems.

The cultures of companies are in turn very different. These can be autocratic, bureaucratic, consultative, participative or even highly participative.

The educational level of the workers depends on the industry type, on the national educational system and on the companies' effort to educate the human resource.

The decision for choosing an optimization program depends on all these factors.

The previous presentation as well as the ideas structured in Table 1 can suggest to the managers, what would be the appropriate methodology for a given situation.

Some ideas can be underlined:

- In companies where there are quality issues and a data history, it's helpful to implement Six sigma; If the company face with a stagnant market or relatively less competition, then DMAIC methodology is useful. When the market is more dynamic and the competition is strong, the DFSS is necesarry because of the need of quality from the very beginning;
- In autocratic companies it is indicated to use TOC;
- In companies where the educational level is high and there is a culture of work, TPS is useful;
- In companies that value the visual information, Lean Manufacturing is suggested;
- For companies that are active in very dynamic and competitive markets, Agile Manufacturing will be applied.

But, with any methodology going on, some more aspects will be improved, even if they have not been targeted from the beginning. In table 1, the primary and the secondary effects of each methodology are underlined.

Smart manufacturing is still a vision that will probably become true sooner than we expect, for large, medium and small businesses. The common framework of standard reference architectures, standardized KPIs, and other Industrie 4.0 facilities will enable companies to optimize their business in a more dynamic way.

4. Conclusions

The paper analyzed the main aspects of the production optimization methodologies developed to date. There were highlighted the main aspects that make them different one from the other, but also the common aspects. This comparative analysis is just a beginning that deserves to be developed in order to support management, in decision making activities.

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