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LEARNING CURVE IN OPERATIONS MANAGEMENT: THEORETICAL AND PRACTICAL ASPECTS

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Abstract: *The aim of the paper is to provide a theoretical review of the understanding of the learning curve, the key areas of its application, and to highlight the learning process behind this phenomenon. In order to achieve this goal, a theoretical analysis is conducted and a review of research and views of the leading authors on selected topics is given. The basic implication is a notion that learning curve can be a useful tool for measuring, forecasting and managing performance, but that it can and should be managed as well.*

Keywords*: productivity, operations management, knowledge management.*

1. Introduction

The phenomenon of reducing cumulative unit costs at uniform rate with increasing experience is widely known in organizational and economic literature (Lapré & Van Wassenhove, 2003; Artur & Huntley, 2005). First it was described by Wright in 1936 after he noticed that costs of assembling aircrafts decreased with the production volume being increased (Fogliatto & Anzanello, 2011; Jarkas & Horner, 2011). Based on empirical data, Wright came to a rule that cumulative average aircraft assembly costs are on average reduced by 20 percent when doubling the production volumes (Howel, 1981; Fogliatto & Anzanello, 2011). Thus, the learning curve was developed as a curve representing a graphical relationship between the time needed to produce a unit of product and the amount of products produced (Jarkas & Horner, 2011). Nevertheless, there is no terminological unity, so different terms such as: cost reduction curve, efficiency curve, progress curve, performance curve, experience curve and alike, are used to name the phenomenon behind the learning curve (Pedersen & Slepinov, 2016). Regardless of different terminology, the base of the learning curve concept is a description of the empirical observation that the amount of resources (men-hours, costs) needed for production decreases with the increase in the production volume (Jarkas & Horner, 2011).

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In order to provide a comprehensive review of the basic assumptions and application of the learning curve and to highlight the process which lies behind it, the analysis of theoretical sources was performed. The remainder of the paper is structured as follows: the basics of the learning curve phenomenon and its application are described in the second section. The logic and the need for managing the learning curves and learning rates are revealed in the third part of the paper, after which the learning process of the learning curve is analysed. Finally, certain concluding remarks are given.

2. The learning curve phenomenon and its application

The learning curve is an analytical tool that quantifies the rate at which the accumulated experience affects the costs of production (Jarkas & Horner, 2011). It is a mathematical description of the workers' performance in carrying out repetitive tasks (Fogliatto & Anzanello, 2011). Whatever the definition, the basic assumption is that the individuals or groups become more effective in conducting repetitive activities (Jarkas & Horner, 2011). Wright noticed that reduction in costs refers to reducing the time required for the aircraft to be assembled. This is an effect of the fact that over time, by repetition of a task, workers become acquainted with the task and the equipment, so they find shortcuts in performing the task, which leads to improvement in the way the task is performed (Waterworth, 2000; Fogliatto & Anzanello, 2011). This effect is a consequence of the ability of people to learn from their experience, or to become more effective in performing repetitive tasks (Jarkas & Horner, 2011). Therefore, this phenomenon can only be observed in situations where the activity is repetitive, continuous, and identical. The theory assumes that the same individuals are involved in performing the repetitive tasks.

After the phenomenon has been observed, mathematical models of learning curve have been developed aiming to predict or measure productivity improvement through repetitive tasks (Jarkas & Horner, 2011). The first formal learning curve model is that defined by Wright and it is known as log-linear model of learning curve (Fogliatto & Anzanello, 2011)[1]. Although not mathematically complex, this model is a good description of manual operations (Fogliatto & Anzanello, 2011), and it is the most widely used and accepted model of the learning curve (Blancet, 2002; Jeang, 2015). Wright's learning curve formula is:

$$y_i = a x_i^{-b} \tag{1}$$

where *y* is the number of labour hours required to produce the *i* unit, *a* is the number of labour hours required to produce the first unit, *x* is the cumulative number of units produced through time period *i*, and *b* is the learning rate (Arthur & Huntley, 2005, 1161). The two basic implications of this formula are that learning has a cumulative effect over time, or in other words, experience gained in a single period affects performance in that period, but also in the following periods. Second, the effect of increasing cumulative production volumes on performance is decreasing over time (ibid.). At the beginning, the learning curve is steep. After this initial phase the slope decreases and after a certain level it reaches a plateau, which means that the additional cumulative production volume does not

[1] For more details on learning curve models see: Fogliatto and Anzanello, 2011; Jarkas and Horner, 2011.

significantly contribute to the improvement of productivity (Muth, 1986; Wiersma, 2007). Howell (1981) states that there are two types of learning curves: the classic straight line and the discontinuous curve. The first one shows the percentage of the reduction in costs for each successive doubling of the cumulative output. In theory, this means that the costs will constantly decrease, regardless of the size of the overall output. In practice, however, the point where further one percent of cost reduction will require a significant increase in the output will eventually be reached, so the curve will became flat. Therefore, Waterworth (2000, p. 29) assumes that the learning curve theory may lose its applicability for higher production volume. The discontinues curve can be found in the machine-dominated processes and it represents the situation in which after a period of time the curve kinks to a new, significantly lower level of improvement, or even to a zero improvement (Howell, 1981).

Aforementioned model of the learning curve reveals a characteristic known as constant percentage reduction, i.e. whenever the output volume increases by a constant percentage, the cumulative average time for producing that volume is reduced by a constant percentage (Waterworth, 2000). For convenience, it is taken that the increase in the output volume is 100 percent. The so-called experience law suggests that the labour hours per unit of the produced volume are decreasing at a predictable rate as workers gain experience in production (Pedersen & Slepinov, 2016). This rate is known as learning rate and it determines the speed of the improvement. For example, the rate of 80 percent means that by doubling the production volume, the input of working hours and consequently the costs are reduced by 20 percent, or they represent the 80 percent of the working time/costs required to produce the initial quantity. Therefore, the higher the rate, the learning is slower, and vice versa (Waterworth, 2000).

Waterworth (2000, pp. 24-26) points out that Wright's learning curve is often misinterpreted. Namely, the learning curve theory defines three graphics: 1. The unit cumulative average graph (average cumulative time needed to produce each unit of a batch against increasing batch size); 2. The unit graph (actual time needed to produce each unit of a batch against increasing batch size) 3. The cumulative total graph (cumulative total time needed to produce each unit of a batch against increasing batch size). Data showed in Table 1 are used to illustrate the difference between these graphs (Figure 1).

Table 1. Data for constructing the learning curve

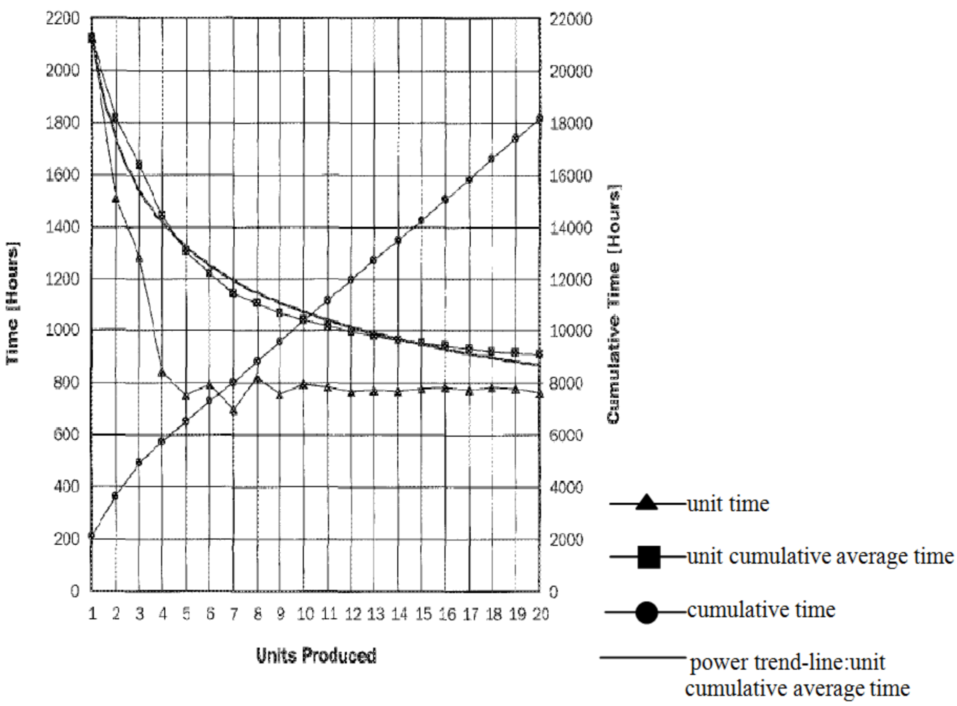
Unit produced (1)	Unit time (2)	Cumulative time (3)	Unit cumulative average time (4=3/1)
1	2122	2122	2122
2	1512	3634	1817
3	1283	4917	1639
4	848	5765	1441
5	755	6520	1304
6	798	7318	1220
7	697	8015	1145
8	825	8840	1105
9	759	9599	1067
10	798	10397	1040
11	788	11185	1017
12	771	11956	996

13	774	12730	979
14	770	13500	964
15	778	14278	952
16	786	15064	942
17	777	15841	932
18	785	16626	924
19	781	17407	916
20	764	18171	909

Source: Waterworth, 2000, p. 25

Note that the unit time does not have to necessarily decrease with the increasing volume (e.g. between units 5-6, 7-8, etc.), while the unit cumulative average time does decrease with every additional volume unit. Wright's basic learning curve formula is an approximation of the unit cumulative average graph (Waterworth, 2000). However, many authors omit the terms cumulative and average, which gives the impression that the equation is about the unit graph, but the truth is that unit cumulative average value decreases with increasing production volumes and the rate of that decrease is the essence of the learning curve.

Figure 1: Learning curve



Source: Waterworth (2000, p. 26)

The learning curve is a tool for quantifying and measuring learning for the purpose of performance improvement and it has a significant application in the production systems

(Fogliatto & Anzanello, 2011; Pedersen & Slepinov, 2016). The most obvious application of the learning curve is for prediction of future costs (Henderson, 1984). The learning curve is used for forecasting due to the discovery that the cost reduction does not happen in a random way, but with a certain regularity that can be described by the learning curve's formula (Zangwill & Kantor, 2000). Also, the learning curve model is used for production planning activities, such as: examining the impact of employees' learning on the inventory policy, determining the optimal lot size, and alike. This instrument is also used in combination with quality control techniques. For example, it examines the relationship between the process of employees' learning and quality control in factories, the impact of the learning rate on the quality and costs of new products, etc. This curve may have an important role in planning, monitoring, controlling and improving productivity (Waterworth, 2000). When used to plan the production costs, it is very important that an organization knows its own learning rate. Determining this rate is the hardest part of using the learning curve. Using a usual or most common learning rate for an industry may result in inaccurate results in a given company (for an example see in: Waterworth, 2000, p. 30). Based on historical data, organizations should determine their own learning rate. However, this rate differs not only from plant to plant, but also in one plant from time to time. Also, one should bear in mind that learning curve should be used only in those processes that have the potential for learning, which are those in which the manual labour dominates (Waterworth, 2000; Jarkas & Horner, 2011). Case research conducted by Blancett (2002) showed that log-linear model of learning curve developed by Wright may be used to predict the performance of new processes, the future performance of current processes, and to identify processes which performance are below their potential.

During the 1960s the Boston Consulting Group has identified the strategic application of the learning curve (Howell, 1981, p. 26). Based on a assumption that the largest cumulative producers have lowest unit costs, they came to a conclusion that larger profits can be realized if the dominant market share could be realized (dominant market share increases the cumulative production volume and reduces costs). Implementing that logic, companies were extremely interested in defending the dominant market share or leaving the markets where they can not dominate. Practically, some large companies have abandoned their minor activities and focused on those in which they dominate. This kind of behaviour led to the weakening of the diversification that was dominant in the 1960s. However, although the learning curve can be a useful tool, it should be used cautiously, as there are exceptions from the rule. For example, dominant companies are not always the most profitable ones. For the strategic purposes, learning curve was used as a basis for the horizontal axis of the growth/share matrix (Henderson, 1984, pp. 3-4). Based on the learning curve implications, market share was used as a surrogate for cost advantage. In line with this, the PIMS research showed that there were high correlation between market share and costs.

3. Management of learning curves

Knowledge of learning curve is not important unless it is used to improve the competitiveness of those who understand it (Henderson, 1984, p. 3). Learning rates can differ not only across industries, but also across companies which have same processes and portfolios, across sectors within one company, or even between different individuals who perform same tasks (Lapré & Van Wassenhove, 2003). This variability raises the question of whether and to what extent deliberate management activities can be implemented in order to improve performance through experience (Arthur & Huntley, 2005). This process of improving the organization's performance by generating, codifying and transferring knowledge in an organization is called planned learning, induced learning or deliberate learning. In other words, the learning curve and learning rate can be managed (Lapré & Van Wassenhove, 2003; Jarkas & Horner, 2011). Management of learning curves and rates can be seen through lenses of knowledge management. Argote, McEvily and Reagans (2003) speak about three mechanisms of knowledge management: ability, motivation and opportunity. Ability to create, retain or transfer knowledge is an inborn ability, but it can also be influenced by training. For example, developing analytical skills facilitates the transfer of knowledge acquired through performing one task. Motivation to crate, retain or transfer knowledge can be stimulated by monetary and social rewards. Opportunity exists when experience allows knowledge to be created through trial-and-error learning. By providing physical and psychological closeness between its members, the organization creates learning opportunities. For example, by observing a colleague performing a task, proximity allows to learn what he/she knows, so knowledge of where to look for information is gained. Transfer of routines, tools and technologies allows organizational unit that receives them to gain the knowledge which was created by the unit that has used them before. Authors cite a study that shows that for achieving better performance is more important to gain experience in observing others while performing a task than classroom training. Individuals who learn by observing others may not be able to define what they have learned but they will be able to transfer and to apply this knowledge when doing the task themselves.

Pedersen and Slepinov (2016) agree that the learning curve needs to be managed, and not only passively followed. These authors point out another very important observation: the final output and the time needed for it to be produced are influenced not only by direct value-adding hours but also by indirect non-value-adding time. The time spent on production (measured in working hours) is also influenced by the time spent on activities that do not directly contribute to production, such as supply, logistics, quality control. These activities are called supporting activities. For example, due to some logistical problems, the production may be disrupted, which can distort the production learning curve. It is therefore important to note that the overall learning curve is not only influenced by the process of learning of production workers, but also by those in supporting activities. That is why establishing stable flows in supporting activities is important for improving the learning curve in production. In other words, it is also necessary to manage supporting activities as they affect the final output and the time required for production. The case study examined by authors showed that errors in the planning phase (such as: warehouse planning, uncoordinated procedures, outdated work instructions) led to the great participation of non-value-adding production time. The conclusion is that it is necessary to plan all areas, not just the production. They also highlight that for the learning curve is important to plan production preparation. Although that the influence of direct working hours on the learning curve and performance is most visible, the case study showed that only 21.9 percent of the loss of time arose due to the problems in the workshop, while the remainder of 79.1 percent originated outside the production.

Understanding the manageability of the learning rate and based on case study research, Wiersma (2007) highlights certain strategies that can be implemented to maintain the learning rate at certain level, after the initial opportunities for improving the process are exhausted. For example, he proposes that workers should be given the opportunity to learn by providing them time and resources for it. He also argues that the ability to learn is not only created by formal forms of training, but also by providing workers with a heterogeneous experience. Finally, he states that temporarily hired workers also contribute to learning. Management interventions focused on the knowledge expansion are important because there is a potential conflict of interests for which employees decide not to share the knowledge they have (Arthur & Huntley, 2005). There are cases where production workers do not want to share their knowledge gained through experience because they fear that this knowledge will be exploited against them or that they will not be adequately rewarded for this.

4. Learning process behind the learning curve

Learning curve is mainly used to forecast costs and other performance and not to increase the learning rate (Zangwill & Kantor, 2000). At the same time, *"the rate at which individuals and organizations learn may become the only sustainable competitive advantage"* (cited by Lapré & Wassenhove, 2003, p. 53). In order to exploit the source of performance improvement, the concept of learning curve has to be understood (Pedersen & Slepinov, 2016). The problem is the fact that the learning curve is an empirical phenomenon and studies mostly recorded it without much explanation of the phenomenon itself (Zangwill & Kantor, 2000). Moreover, the learning rate is treated as an exogenous variable (Lapré, 2011). But, as it can differ from industry to industry, between different companies within the same industry, and even between different organizational parts of the same company, it may be concluded that this rate should be treated as an endogenous variable. In other words, the learning rate is a variable that management can influence. The main problem is that in most of the studies learning curve is considered to be a black box, and there is no much of analyzing the actual learning process behind it.

The basic premise of the learning curve phenomenon is that individuals and organizations learn through gaining experience (Arthur & Huntley, 2005). Experience is usually measured by cumulative production volumes or by calendar time[2]. Production experience generates knowledge that affects performance improvements. Two basic learning mechanisms constitute the organization's learning process: autonomous learning (or: learning-by-doing, first-order learning, informal learning, behavioural learning) and deliberate learning (or: second-order learning, formal learning, explicit learning, induced learning) (Muth, 1986; Adler & Clark, 1991; Arthur & Huntley, 2005; Wiersma, 2007; Lapré, 2011). Former mechanism implies that knowledge is acquired through repetitive performance of tasks by individuals or groups. It means that workers learn by trying different ways to perform tasks in order to find those which are most efficient. One of the most prominent features in the learning curve's considerations is that it is related with experience acquired through repetition of tasks. Lapré (2011, p. 26) cites Skinner's *focused factories* which outperform those performing a wider spectrum of operations due to homogeneity of tasks and higher repetition rate. However, certain studies show that different but related experience is even more important than specialization for increase of

[2] Elaborating on the sources of learning, Lapré (2011, p. 25) states that most commonly used proxies for experience are: cumulative production volume, calendar time from the start of performing a task and maximum output produced to date.

the learning rate. Although this kind of experience may compromise the short-term productivity, it improves it in the long run. Wiersma (2007) hypotheses that the ability to learn is greater when employees have a diverse experience or when they are assigned different but related tasks. He confirms this hypothesis and concludes that processes are holistically perceived when there is a diversified experience. Moreover, the ability of an employee to transfer successful routines to related tasks is increased when the experience is diversified. Besides, Wiersma (2007) finds that ability to learn is positively affected by certain level of temporary engaged workers, while the excess capacity improves the opportunity to learn. Namely, an organizational code consists of procedures, norms and rules of conduct in the organization and it is created by accumulating knowledge. Members of the organization learn from this code and they can improve it if they have superior knowledge. Those members that are longer in the organization become socialized to the code and less likely to change it. If the system is closed and there are no new members to join, members remain more socialized and similar to each other so that at some point there is no further improvement of the code. This can be changed by introducing new members. Employees with long experience in an organization really know more, but their knowledge has already been incorporated in the organizational code and it is redundant in that respect. On the other hand, new members on average know less, but their knowledge is more important for the improvement of the organizational code. By introducing new members (temporary workers), existing workers can learn from them how a task can be performed in a different way, and also become aware that the existing way for organizing the work process is not the only one. As to the excess of the capacity, Wiersma (2007) argues that when there is excess of the capacity, workers have time to explore new ways of doing their current job. When the capacity is limited, the usual procedures are followed.

The second mechanism of learning refers to the planned process for acquiring, codifying and transferring knowledge in organizations. Induced learning involves: training, product design changes, acquisition of new technology, etc. This type of learning is triggered by higher level of management and is known as Learning process model or double-loop learning (double-loop learning can inhibit single-loop learning by continuously introducing new procedures and technologies to avoid repeating the same tasks).This mechanism influences the ability, motivation and opportunity for the experience based learning to occur. Adler and Clark (1991) state that first mechanism of learning is traditionally captured by the experience variable in the learning curve models. Nevertheless, they propose a Learning process model which recognizes the importance of the second-order learning. Part of the effects of the experience on the productivity which is registered by the learning curve is a result of the second-order learning, which is again the result of explicit and intended management actions (such as: changes in product design through engineering changes and development of the human capital by training). It is important to note that these deliberate management activities may have both, positive and negative impact on productivity. For example, if engineering changes are undertaken with a primary goal to improve the productivity, then they will do that. But, if they these changes are implemented in order to improve certain performance of the product, then they can jeopardize the productivity (at least in the short term).

Speaking about learning in general, Lapré and Van Wassenhove (2003) distinguish two different aspects of learning. One of them is conceptual learning which refers to the process of understanding the relationship between causes and consequences. This kind of learning presupposes application of scientific models and statistical calculations in developing concepts and theories to explain the cause-consequence relationship. Conceptual learning results in know-why, while the other aspect of learning, named operational learning, results in know-how. The learning process is multidimensional, so one dimension can be less and the other more pronounced in different projects/tasks. Researching the capacity of local learning (learning that occurs in one project/task) to improve the knowledge of the organization, authors differ four categories of projects. *Firefighting* is used to label the projects in which both dimensions of learning are low. These projects do not affect the global rate of learning. *Artisan skills* are projects which are closer to art than to science. They create know-how because they have a high level of operational learning. However, these projects have a low level of conceptual learning. This means that there are practical solutions that yield results, but there is no understanding why this is happening. That is why this knowledge is difficult to transfer to other projects and parts of the factory (because the logic of the solution is not understood). These projects have little impact on the global rate of learning as well. Projects that are characterized by high level of conceptual learning authors name *non-validated theories*. These projects generate high level of conceptual learning, so they reach solutions in a theoretical and conceptual sense, but these solutions are not validated in practice. Surprisingly, these local non-validate theories slow down the global rate of learning. This happens because many of these solutions have been developed in the research and development sector and they fail to be successful in the real environment of the factory. Finally, the *operationally validated theories* are the only ones that contribute to the improvement of the global rate of learning. Based on scientific principles, solutions and theories are developed which are then validated in practice. These projects create transferable principle and knowledge because solutions have been developed on scientific basis and the cause-effect relationship is understood (the logic of why a solution works is clear).

Causal and control knowledge are in relation to aforementioned aspects of learning (Lapré, 2011, p. 31). Causal knowledge is the knowledge about the relationship between input (*x*) and output (*y*), while the control knowledge measures the level in which an organization is able to keep the input variable at the desired level. Both the causal and the control knowledge are gained through a learning process with certain phases. The causal knowledge is acquired through conceptual learning, while the operational learning leads to control knowledge. The causal knowledge begins with the *ignorance* phase, at which an organizations is not aware that there is a causal relationship between *x* and *y*. At the next level, the *awareness* phase, the existence of the relationship is known, but the direction of the causality is not. That *x* affects *y* is known at the third, the *direction* phase. At the *magnitude* phase, the organization can measure the impact of *x* on *y*. At the fifth stage, the phase of *scientific model*, the organization can develop a model with parameters describing the relationship between *x* and *y*. Finally, at the *interaction* phase, the organization has knowledge about the interactions with all other input variables. The process of gaining the control knowledge also begins with the *ignorance* phase at which the organization doesn't know that the *x* exists. At the *awareness* stage, the organization is aware of the existence of *x*. The *x* is measured at the third, *measured* phase. At the *control of the mean* phase, the organization controls the mean level of the *x*, but there is a significant variation of the level of the *x*. The variance of the *x* is controlled at the fifth, *control of the variance* stage. Finally, at the *reliability* phase, the organization can always maintain the desired level of the *x*.

5. Conclusion

The learning curve concept captures the empirical phenomenon of reducing the average cumulative costs with increased production level. Wright was the first one to record decrease of the production costs by a constant percentage with the increase of the output volume by a constant percentage. This became known as the constant percentage reduction, or the experience law. As Waterworth (2000) remarks, it is important to keep in mind that the classic Wright's learning curve formula is an approximation of the unit cumulative average graph and not of the unit graph. After being recorded in the aircraft industry, the experience law was observed in other industries as well and has been used for various management purposes, such as: planning, quality management, human resource management, etc.

The predictable rate of cost reduction with accumulation of experience is the rate of learning which determines the speed of performance improvement. Although it is often treated as exogenous variable, there is enough empirical evidence that shows that this rate can vary across industries, companies from the same industry, units within the same company and even individuals on the same task. This means that learning rate may be seen as endogenous variable, or variable that can be managed. Cumulative production volume and calendar time are almost exclusively used proxies for experience in the learning curve models. Nevertheless, studies show that when managing the learning curve and the learning rate, two basic mechanisms of acquiring knowledge should be considered: the autonomous learning and deliberate learning. While the first mechanism is traditionally captured by the experience variable, the second one is included only in the extended models of learning curve, or in the learning process models. This deliberate learning consists of various planned and deliberate management activities aimed at generating, codifying and transferring knowledge. These activities, such as: changes in product design through engineering changes and development of the human capital by training, can also enable and/or accelerate the process learning-by-doing. Thus, deliberate learning can affect the learning curve and the learning rate. When undertaking activities in order to produce certain knowledge, it is important to know that only the knowledge that has both conceptual and operational dimension may improve the global learning rate of a company.

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KRIVA UČENJA U OPERACIONOM MENADŽMENTU: TEORIJSKI I PRAKTIČNI ASPEKTI

Apstrakt: Cilj rada je da pruži osvrt na teorijski tretman krive učenja, na ključne oblasti njene primene, te da osvetli proces učenja koji je u osnovi ovog fenomena. Kako bi ovaj cilj bio ostvaren, izvršena je teorijska analiza i dat je prikaz istraživanja i stavova vodećih autora po izabranim temama. Osnovna poruka je da kriva učenja može biti koristan alat za merenje, prognoziranje i upravljanje performansama, ali da se i samom krivom učenja može i treba upravljati.

Ključne reči: produktivnost, operacioni menadžment, upravljanje znanjem.