The Analysis Of The Low-Cost Flexibility Corridors

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Abstract—**The study puts forward a proposal for the method of determining the so-called corridors of low-cost flexibility (the flexibility at the lowest cost possible), which enable the system flexibility and leanness levels to be balanced out at the lowest possible costs of maintaining the operational flexibility of the entire manufacturing system. For this purpose, simulation modeling was used, whereby, based on data from the object of examination, the savings were determined, which are capable of being generated in the case of conducting operational activities in a defined flexibility corridor. Obtaining the capability to define the low-cost flexibility corridors will allow the system's operational flexibility to be maintained at the lowest possible cost.**

Keywords—manufacturing system flexibility, low-cost flexibility, flexibility corridor

I. INTRODUCTION

The low-cost flexibility of a manufacturing system is such a combination of organization elements that leads to the balancing of the system flexibility and leanness levels. A basic problem in the balancing process is that both the flexibility and the leanness of manufacturing exclude each other (i.e. what is lean cannot be flexible, and vice versa). The wish to maximize the flexibility and leanness levels at the same time results in a conflict of interests of "*system elements*", which can be reduced by increasing the level of agility of the entire manufacturing system. By making the assumption on the capability to balance the leanness and flexibility levels, it is possible to determine the flexibility corridors, and thus to minimize the costs of operational flexibility for the entire system.

II. MANUFACTURING FLEXIBILITY

From its practical aspect in manufacturing, flexibility with an economic origin (flexibility as a function of costs) was only considered in the concept of combining small, functional machines [1]. On account of excessive specialization in manufacturing, it was not until the 70s and 80s of the 20th century that flexibility gained importance and became one of the elements of winning competitive advantage. Manufacturing flexibility (most often considered also in the economic and operational aspects [2]), is a complex, multi-dimensional category [3], and therefore it can be determined in a different manner [4], [5], and, as a consequence, interpreted differently. The analysis of selected definitions of flexibility [2], [6-17] (understood either as an attribute, feature, function, etc.) enabled the adoption of its universal definition. Flexibility, belonging to one of the five manufacturing changeability classes [10], is defined as the operational/tactical ability of the entire separated manufacturing area (segment/system) to quickly change the components into new or similar groups, which is achieved by a small effort and in a reasonable time by changing the processes (flows). Manufacturing flexibility, as opposed to reconfigurability, is understood as the ability of the entire segment/system to change without changing its own configuration, which is possible at a higher level of complexity (e.g. agility). The analysis of the definition shows that the flexibility of manufacturing as a component of the enterprise's flexibility [18] can be understood as the ability to react to (internal and external) changes, which boils down to the purposeful and economic maintenance of the reserves of specific resources (redundant resources relative to the current needs) to be used at any convenient time (e.g. when an opportunity arises – the condition for using the opportunity is, inter alia, to have resources available and, actually, their excess or, at least access to them). Manufacturing flexibility is also the ability to react [19] to the occurring uncertainty in such a manner that either maintain or increases the system's parameters in the area of the times and costs of functioning. Assuming the most general division of manufacturing changeability, flexibility relates to the operational level (the level of the segment/module and its less complex parts).

III. OPERATIONAL MANUFACTURING FLEXIBILITY

Flexibility is associated with predictable changes, both internal and external (but within the area of the defined structure), so it is justifiable to assign it, by assumption, to the system's operational levels [15], for which the relative stability of functioning conditions is a desired feature. Stability is a feature of the system that arises from the ability to independently overcome changes in output states without having to change the structure in the assumed area (corridor) of flexibility. Changeability (most often in the environment) causes a disturbance of the system, which responds trying to return to the original state. As a rule, the response is instantaneous, because the system tends to equilibrium and will not tolerate well its opposite. Imbalance is a state of the system, in which no changes occur, either in the system's structure or in the conditions that define this state. Depending on its structure, the system may have one or more points of equilibrium. Attaining a new equilibrium point is only

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possible by means of changing the system's structure, that is changing the corridor into a more variable one (Fig. 1).

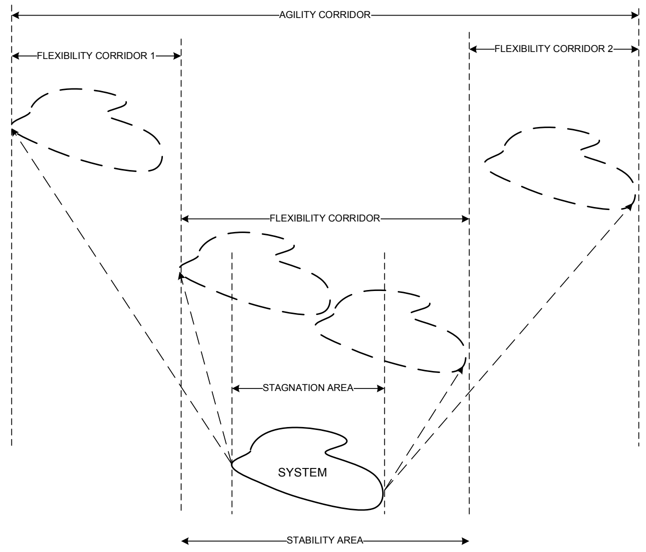

Fig. 1. Corridors and areas of the system

In manufacturing systems, an increase in flexibility at the operational level (so-called operational flexibility associated with the scope of the possibilities of changes in the area of the resource, process or production plan [16]), is most often achieved as a result of the increase in:

- resource flexibility. Resource flexibility is closely related to resources occurring in the manufacturing system [20], [21], primarily material ones, and the possibility of changing/replacing them, as well as their redundancy. Regardless of the exogenous or endogenous perspective, flexibility is largely determined by the redundancy of resources, access to foreign resources, and their internal flexibility. The flexibility of resources may also concern the systems of resource planning and control, defining the method of their reciprocal use and coordination;
- process flexibility. Process flexibility is associated with the possibility of changing the course of manufacturing processes within the existing structure. This flexibility means the possibility of carrying out different process configurations, depending on the current needs, on the assumption that output parameters do not change. Process flexibility is also associated with the flexibility of operations carried out on individual resources;
- planning and control flexibility. Planning flexibility is related to the ability to configure alternative production plans within the defined product line group, used in specific situations. Control flexibility is connected with the ability to respond in an ongoing manner in the case of any deviations from the plan, resulting from disturbances of the flow. The flexibility of planning and control systems enables also ongoing changes related to the principles of inter-modular cooperation, and thus to creating different systems of relationship: hierarchical, heterarchical or holarchical. This flexibility is also connected with the type of software used for ongoing planning, and in particular flow control;
- and, indirectly, structural flexibility (only in the case of dynamic systems within the predefined corridors and permissible changes) and functional [16] (the ability to perform a variety of tasks and means a combination of resource and process flexibility). Structural flexibility concerns only the possibility of changing the mutual order of elements making up the so-called structure of manufacturing organization and their interrelations. Most often, however, structural flexibility contains operational flexibility.

Flexibility on the operational level may apply to all manufacturing system areas; most often, however, the following are distinguished: the product area (e.g. constructional or technological flexibility), the technology area (e.g. machinery or route flexibility), and the area of the system and its organization (e.g. product line, plan or cooperation flexibility). Due to its operational nature, flexibility is measurable, and the formulas for its calculation and its necessary level are provided in numerous studies, e.g. [6], [12], [23], [24]. The analysis of flexibility calculation formulas indicates their great variety, which results from the adopted definition of flexibility. It is proposed to assess flexibility based on two factors [25]: the speed of responding to changes and the cost of responding to changes.

IV. Flexibility Corridors

The operational flexibility of manufacturing represents the ability to respond to changes within the defined scenario or the predefined response to foreseeable changes without changing the structure arrangement. A higher level of system (class) changeability than that of flexibility allows one to leave this predefined corridor of changes without having to expend a considerable financial and time effort [22]. Depending on the scope of changes, manufacturing systems should function in changeability corridors, including flexibility corridors. A problem is, however, to define the boundaries of individual corridors, as well as to define the best formula for the evaluation of the changeability cost, e.g. [26], [27]. In view of the costs of changeability (achieving and maintaining), the most advantageous is to maintain the system within flexibility corridors (Fig. 2 - based on [13]).

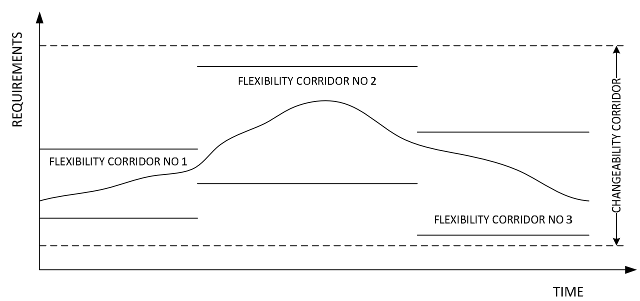

Fig. 2. Flexibility and agility corridors (changeability corridor)

On the operational level, any change going beyond the boundaries of the flexibility area (purposeful or sometimes unplanned) involves additional costs of manufacturing system operation; therefore, constant expanding and shrinking of changeability corridors is found in practice (Fig. 3 - based on [26]). This is associated primarily with the incomparably higher costs of maintaining a system within a corridor of a higher-class changeability (e.g. agility), compared to the costs of maintaining flexibility corridors. As a rule, the higher the changeability class of a manufacturing system, the more difficult is to estimate the variability of the system (the return on investments is difficult to estimate and not always accurate [28]).

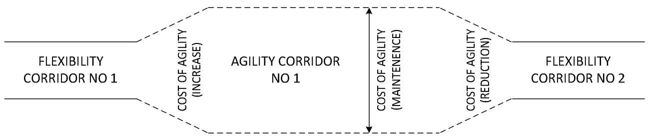

Fig. 3. Costs of changeability corridors

V. Low-Cost Flexibility Corridor

The main emphasis in contemporary manufacturing is placed on flexible adjustment to customers and their unique needs. Its core is both the speed of responding to new market opportunities, as well as the costs and quality of finished products that the customers are willing to purchase [29]. It is therefore essential to skillfully balance the level of flexibility and the cost of maintaining it in current activity, that is to achieve low-cost flexibility. The low-cost flexibility of a system is the flexibility achievable at the lowest cost. As a rule, increasing the flexibility level results in an increase in system operation costs, whereas reducing the costs causes a stiffening of system functioning. What determines the essence of flexibility is achieved owing to additional costs generated by maintaining the system in the state of readiness for the variation of routes, technologies, production volumes, etc. Flexibility is maintaining resource and organizational reserves in case of any sudden and unforeseeable changes, which means that increasing the effectiveness takes place at the cost of reducing the so-called leanness (Fig. 4 - based on [30]).

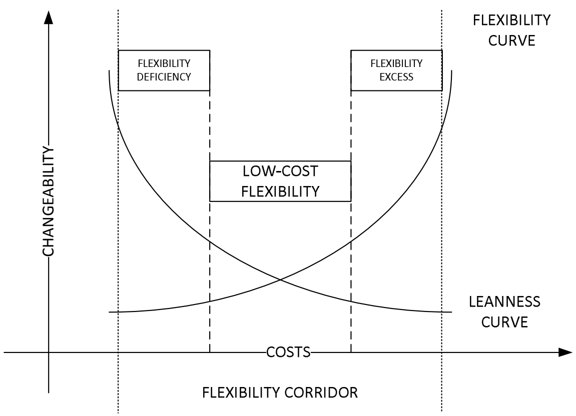

Fig. 4. Low-cost flexibility

Leanness in manufacturing means eliminating all unnecessary activities and leaving only those that represent the core of the company's activity. A starting point for attaining leanness is the ability to perceive wastage. In improvement processes, wastage is assessed and its reduction results in a lowering of the costs of functioning of the entire system. A basis for determining the leanness is also the so-called added value generated in the process of manufacturing a product or providing a service. The added value is what the customer is able to pay for, with the difference between the added value and the real cost constituting an area for potential cost reduction. What is, among others, an indicator of lean manufacturing, including [31]: the integrated flow of a single product piece, the low (zero) inventory level, small production series, just-in-time manufacturing, standardization, continuous pull system production, manufacturing for the customer's current needs, generates a decrease of the system flexibility level. In practice, the "*leanest*" manufacturing systems are inflexible, automated linear systems optimized for the production of a single product line. It is very hard to achieve increased operational manufacturing flexibility, while increasing so-called leanness (cost reduction). There is, however, a possibility of determining the time interval, within which maintaining flexibility redundancies is economically justifiable.

VI. The Cost Of Low-Cost Flexibility

Maintaining costs within the area of the low-cost flexibility corridor should balance out the flexibility and leanness costs. The costs of operational flexibility is the sum of the costs of:

- resources necessary for the ongoing execution of tasks, as well as their redundancy,
- real processes and their alternative (virtual) flows (the costs of operations possible to be taken into consideration),
- preparation of plans and ongoing flow control, along with their possible modifications.

The costs of leanness is the sum of the costs of elimination of the individual categories of wastes [32]:

- overproduction (the costs of maintaining and operating the area, maintaining inventories, cash freeze, etc.),
- inventories (the costs of maintaining and operating the area, stock accumulation, cash freeze, etc.),
- defects and rejects (the costs of materials, reworking, labour, etc.),
- redundant motions (the costs of labour, tool operation, etc.),
- processing (the costs of labour, hall and machinery operation, etc.),
- waiting (the costs of labour, area maintenance and operation, means of transport, etc.),
- transport (the costs of labour, area maintenance and operation, means of transport, etc.).

In practice, all necessary data can be easily acquired or estimated, provided that the appropriate costing is used. A dedicated costing method for determining the low-cost flexibility is activity-based costing. Making the ongoing, dynamic statement of leanness and flexibility costs is practically impossible without computer support. Such a capability is provided, e.g., by simulation modelling which, by performing a series of simulations on variable system configurations, enables the determination of their most advantageous arrangement. The most advantageous system configuration, in given conditions, becomes a model, at which the system should aim (the point of equilibrium between flexibility and leanness). The difference between the model solutions and the actual solution is referred to as the improvement potential. Determining the potential value enables one to determine the degree of deviation of a system's organization from the state recognized as the most advantageous. To determine the potential, two states of the systems need to be defined: the actual state and the model (target) state, and then compared with one another. States can assume numerical values either inside the range of changeability of a feature, or at its boundaries, and can also be obtained using a simulation model.

VII. Simulation Experiment

To verify the proposed method of determining the low-cost flexibility corridors, a simulation model of the manufacturing system - final assembly area in the automotive industry was built. For this purpose, the Witness software and an in-built optimization ("*adaptive thermostatistical*") algorithm incorporated in the Witness Optimizer module were employed. The analysis was based on historical data from 20 periods - planning days (1 day=22 hours) for a fixed group of similar products (car lamps). The method of model operation is illustrated in Fig. 5.

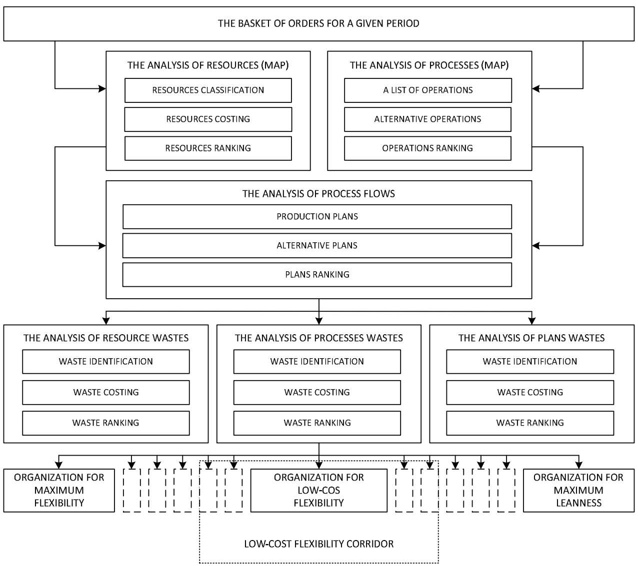

Fig. 5. Procedure of determining the low-cost flexibility corridor

The procedure was started by making a list of all resources and processes necessary for carrying out the orders. The resources were priced in terms of the cost of their maintenance, while the processes, in terms of the costs of their execution. The resources and processes were then ordered according to the criterion of decreasing cost (rankings). Then, the analysis of process configurations possible to occur and their operations (operations adding a value/losses) and resources for a given period was made, while determining the cost of a given variant and the amount of consumed resources and the value of generated wastes. On account of the possibility of involving various resources and various operations for executing the same plan, alternative execution plans were developed. The alternative plans were made by gradually limiting the resources (in the first place, the most cost-intensive ones) and gradually limiting the wastes (in the first place, the most cost-intensive ones). For each plan, the costs of consumed resources and generated wastes were determined (two criterion functions were optimized in parallel in the system: the minimization of the generated waste cost and the minimization of the resource maintenance cost). Based on the historical data, the organization conditions were reproduced, and the amount and cost of consumed resources and the type and cost of wastes generated in the processes were determined in the validated model. Thus, a plan of the organization of the runs of processes under real conditions was obtained. As a result of subsequent operations on the simulation model, the following were obtained:

- a plan of the organization of the flow of processes of the maximal flexibility (no limitations on resources - a theoretical plan),
- a plan of the organization of the flow of processes of the maximal leanness (no limitations on any wastes - a theoretical plan),
- process flow organization plans configured from different combinations of resources availability (flexibility) and wastes generated in the processes (leanness) – 17 plans were generated, thus creating flexibility and leanness levels.

VIII. Simulation Determination Of The Corrodor

As a result of the performed analysis of the maps of processes and the wastes resulting from them, 17 contractual ranges of changeability (resource and waste reduction ranges) were selected. For each of the ranges, a simulation experiment was carried out, thus obtaining a process flow plan and the values of model parameters, including costs. The values of generated costs in respective plans (for each of the 17 ranges) were juxtaposed with each other. The results averaged of 20 periods (days) are illustrated in Fig. 6.

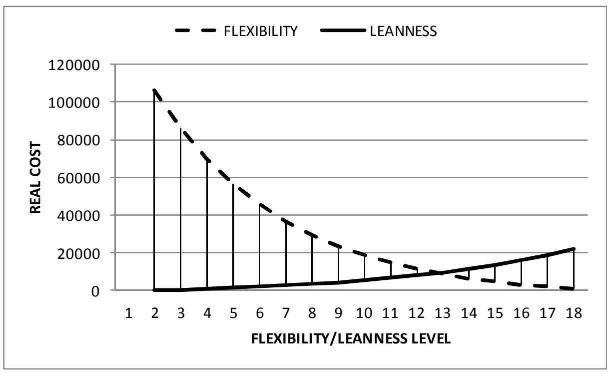

Fig. 6. Flexibility and leanness real costs

As can be seen in Fig. 6, the averaged point of equilibrium between flexibility and leanness has been attained for the 12th level of flexibility and leanness. This is the point at which the lowest costs associated with maintaining involved and redundant resources and generated wastes are achieved in total. Then, for each simulated period separately, the equilibrium points were determined. The positions of the successive equilibrium points and the suggested span of the low-cost flexibility corridor (11-13) are shown in Fig. 7.

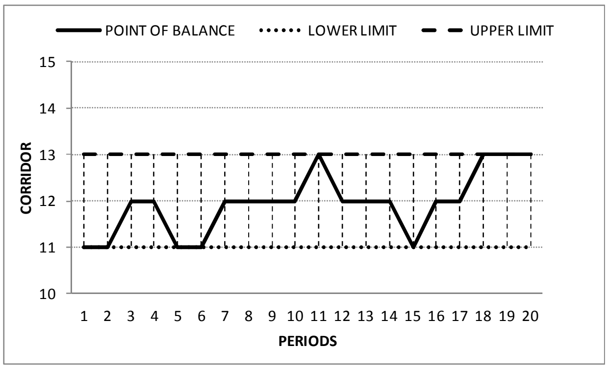

Fig. 7. Low-cost flexibility corridor

The suggested corridor span is determined by juxtaposing the minimal and maximal values of equilibrium points from individual periods, or by imposing predefined cost limits. The cost limits can be determined from simulation experiments (Fig. 8) or by determining the maximal and minimal values allocated for maintaining redundant resources or losses.

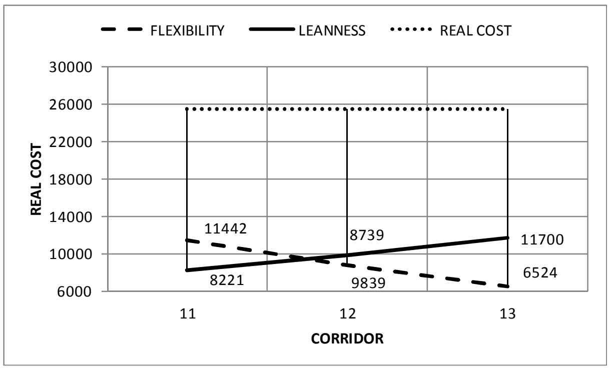

Fig. 8. Cost limits

As indicated by Fig. 8, the cost limits (the corridor ranges for the average values of 20 periods in EUR) should be contained in the range from 18224 to 19663. These are the values of the total costs incurred at the equilibrium points at the upper and lower corridor boundary. So, the cost span between the averaged equilibrium point and the corridor boundaries is: 354 for the upper boundary and 1085 for the lower boundary. The juxtaposition of the real cost value with the cost value at the equilibrium point enables the establishment of the maximal cost reduction value possible to be obtained (7276) and the determination of the improvement potential (the area between the real cost line and the leanness and flexibility curves). The performed analysis provided also the percentage shares of individual cost components. In the research object under consideration, the percentage resource involvement and maintenance share of the total flexibility costs was 79%, the process cost constituted 9%, while the planning and flow control cost accounted for the remaining 2%. The percentage shares of the total leanness costs were as follows: inventories, 72%; transport, 14%; overproduction, 6%; waiting, 3%; processing, 2%; defects and rejects, 2%; and redundant motions, 1%.

IX. Concluding Remarks

The simulation experiments carried out have demonstrated that there is a possibility of determining the low-cost flexibility corridors, provided that there is a possibility of acquiring detailed data from the cost accounting. By juxtaposing historical data (for the real cost and the cost possible to be obtained, contained within the corridor), it can be found that in the case under analysis it was possible to make a different plan of process flows, which would reduce the total cost of execution (EUR) of that plan by 29% and shorten the order basket delivery time by 12%.

The analysis of the components of individual costs and their percentage share of the total cost allows the omission of those components in the analysis, which affect the total cost to a little extent. This will simplify and accelerate the obtaining of the most advantageous solution and generate the suboptimal minimal cost of achieving the low-cost flexibility of the system and determining the span of the flexibility corridor.

Having historical data available, one can also simulate process flow plans possible to occur in the future and analyze them, thus selecting an equilibrium point that is the most favourable (optimal) or is contained in the low-cost flexibility corridor. The selection of a process flow plan from the plans contained within the corridor will guarantee the cheapest possible method of balancing out the flexibility and leanness of the system.

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