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FLEXIBILITY APPROACH IN CONSTRUCTION PROCESS ENGINEERING

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Abstract. The issues of environmental impact on building processes constitute a permanent aspect of the building industry, irrespective of various preventive actions (prefabrication, robotics etc.). The proposed method was developed in the course of tracking problems that arise during performance of building processes exposed to weather impact (as an example of interruptions) on construction sites of airports, highways, logistic centres, or installation of tall building facades. The proposed approach is based on creating multiple variants for process realization options, thus enabling adaptation to current realization conditions at particular stages. The studies that have been carried out confirm the advantage of this method over the traditional planning based on a single realization variant.

Keywords: flexibility management, construction engineering, construction process, planning and monitoring.

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1. Introduction

The basic problems in terms of building process engineering are interruptions occurring on the operating level, derived from risk and uncertainty. This is a specific aspect of the construction industry; in other fields of the economy, risk and uncertainty typically occur on higher levels of management (Ustinovichius *et al.* 2006a, 2006b, 2007; Shevchenko *et al.* 2008; Schieg 2007; Zavadskas *et al.* 2008). Such interruptions often result in delays, downtimes, disputes (Keršulienė 2007), correction works, additional works, high variability in resource utilization (Kaplinski, Janusz 2006) etc. The related losses may apply equally to costs, time, reliability and other factors that are significant not only for the contractor's current effects but also influencing his competitive position. Therefore, it seems justified to flexibly adapt

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to the environment in order to limit non-conformities between planning and realization of building processes, which is very important not only for the contractor executing the studied sequence of processes but also for the coordinator of the remaining dependent processes.

Basic general reasons for implementing flexibility may include:

- Excessively rigid quality management systems (no possibility to implement changes).
- Nonconformity between planning and actual realization, causing difficulties in estimating the costs and duration of building projects execution.
- Operating in increasingly adverse environments (e.g. overcoming technological obstacles).

From the perspective of the above-mentioned problems that arise in planning and realization of building processes, new opportunities should be considered in the following fields:

- collection, transmission and management of data,
- gathering knowledge and learning from examples,
- development of building technologies (e.g. modification of construction materials),
- foreseeing interruptions and monitoring processes in progress (e.g. weather forecast, hardware positioning).

The key factors supporting the implementation of the proposed solution are the increasing opportunities for physical impact on risk and uncertainty immediately at its source, i.e. at the operational level. Flexibility is a commonly encountered quality in everyday life, of key importance for biological survival, however hard to define because of its extensive range of application. In building process engineering, application of flexibility is focused on adaptation to variable production conditions, while the main point in typical flexible production systems is the adaptation of production range to the market requirements. The definition in terms of decision-making seems adequate to the described application in the building industry: the number of optional alternatives left over after one has made an initial decision (Mandelbaum, Buzacott 1990). The overall definition corresponding to the characteristics of the construction industry was given by Stabryła (2005): "flexibility as the opposite of rigidity is a quality enabling effective functioning of a system in terms of existing external conditions and with respect to internal operating capacity, its focus depending on the level of initiative and the system's self-management capacity. Flexibility is therefore a specific form of system efficiency and a measure of its independence: it is determined for purposes of maintaining the balance, which may be the volume of effects and/or functional indicator of the system, such as resistance, reliability, or operating intensity".

The fundamentals of the presented approach are based on the systems theory assuming maintenance of balance in a system through responding to risk and uncertainty on source level. Therefore, flexibility management hierarchy must be considered. On the operational level, risk can be influenced proactively and physically through introducing an appropriate range of technological and organizational variants. These include both options focused on using opportunities (e.g. process conditions are more advantageous than originally assumed) and threats prevention (e.g. implementation of thermal insulation shields preventing low temperature impact) which may seem to be significantly more effective and efficient than reactive options, where the basic functional level is the project coordinator level and which primarily occur in the form of financial and time buffers.

When analyzing opportunities for implementing flexibility, one should consider its two basic types, which are denominated differently by various researchers, but can be most comprehensively classified as active and passive. In developing the proposed method, the terms adaptability and robustness have been used, but one can also encounter numerous other phrases depending on the assumed application concept. These are given in Table 1.

Table 1. Two kinds of flexibility

Source	Active flexibility	Passive flexibility
Mandelbaum (1978)	Action The ability to respond to change by taking an appropriate action	State The innate capacity to function well in more than one state
Eppink (1978)	Active The response capacity of the organization	Passive The possibility to limit the relative impact of a certain environmental change
Evans (1991)	Agility Offence ex ante action	Robustness Defense ex ante action
Presented conception	Adaptability	Robustness

Taking into consideration all different conceptions of flexibility introduced in Table 1, one should underline well-known Eppink's (1978) approach, which sources it has been possible watch in criticism straight line maxim depending on "notes putting all eggs in a single basket". This maxim guides to limitation of consequences of potential changes in environment on working the organization only. Aside from this whether her implementation will depend on diversification of products / services offered by organization or else, it is possible the working the organization in several segments of market, this approach simultaneously must be qualified as passive one. It depends on answer to observed changes. Similarly, in construction management the buffers operate (as time and cost buffers), which aim is creating the possibility of possible disturbances compensation. Applying buffering at organization, it is allowed to reach the reduction of uncertainty/risk to an acceptable level. Eppink's conception includes, however, both components of flexibility: active and passive. The very large emphasis on working proactive sets also Evans (1991), which distributes possible strategies of working in 4 groups in dependence on active or passive approach as well as the moment of acting (before or after it appearing the key event). Short definitions of two components of flexibility (Mendelbaum 1978) give both the right characteristic of flexibility in accordance with accepted in the presented conception. Introduced in Table 1 conceptions of partition of flexibility on 2 components do not write oneself out all possibilities of course; however, they can underline the meaning of proactive approach in flexibility management. It seems that particularly in construction process management such an approach stands a chance for large movement in efficiency and effectiveness of operation with regard to still predominant steering in search of one of the best solutions.

2. Fundamentals, purpose of the proposed method and potential advantages

The presented flexibility approach is based on some well-known theoretical foundations:

- the theory of contingency,
- the theory of organizational equilibrium,
- the law of requisite variety,
- the general systems theory.

The theory of contingency, according to which the correct actions in the sphere of management depend on particular parameters connected with a given situation (Bartol *et al.* 1996), is the opposite of the theory based on the search for universal principles applicable to any situation. It should be emphasized that the first approach to the subject of contingency introduced by Burns and Stalker in 1961 (Burns and Stalker 1961; Morris and Pinto 2004) and developed by Lawrence and Lorsch in 1967 (Lucey 1995) had evolved into the dynamic contingency understood not as adjustment in reaction to triggering event, but also as the application of proactive attitude (Volberda 1999). The idea of organizational equilibrium and the law of requisite variety are closely linked (Gazendam 1993; Gazendam and Simons 1998). The maintenance of equilibrium is more profitable from the point of view of the organization, since the costs of organization functioning outside the state of equilibrium and the costs of restoring the equilibrium justify such a course of action (it concerns the situations, where the losses connected with not achieving the planned results of construction processes, are relatively high in relation to the costs of activities necessary for the equilibrium to be maintained). The law of requisite variety [Ashby's Law (Booner 2003: 341, Lewis and Stewart 2003)] defines 2 conditions for maintaining the equilibrium of the system at a given stage: (1) the system had to remain in equilibrium at the preceding stage, and (2) the necessary diversity of controlling actions has to be available (equal or higher than the diversity of variables characterizing the environment). One of the fundamental assumptions of the theory of systems (Boulding 1956) is based on utilization of the possibility to achieve equilibrium in the system through decentralization (Piotrowski 1995). According to that assumption, on quick restoration of equilibrium and efficient adjustment to changes are possible only when proflexibile actions are undertaken at the place of potential disturbances at their source or close to it. It is justified, therefore, to create quasi-autonomous subsystems, which relieve the higher management problems by providing the most efficient actions at the processes level. The second assumption of the theory of systems, directly applicable to the proposed approach, consists in focusing on the key areas, as opposed to multidirectional activities. A consistent application of that assumption when implementing flexibility means the analysis of risk and uncertainty factors in order to define the most significant one (for which appropriate activity options and tactics are generated afterwards). In relation to the remaining risk and uncertainty factors other methods could be used – e.g. the traditional reactive compensation of disturbances by creating time and cost buffers.

Analyzing various concepts connected with the proposed approach one can distinguish the following:

- the concept of buffering introduced by Kaplinski in 1978 while studying the problem of harmonization of cyclical construction processes (the practical application was based e.g. on intermediate containers for ready-mixed concrete);
- the possibility of application of the principles of functioning flexible production systems in the concrete industry (Reichelt 1987);
- adjustment of the concept of flexible production, previously connected with diverse activities (e.g. from designing and prototype production to computer-controlled manufacturing) to the construction industry (Halpin 1988), upon the example of processing stone materials;
- the activities aimed at reduction of non-homogeneity by the superposition of construction processes, illustrated with examples concerning production concentration;
- flexibility principles applicable to organizational strategy (Volberda 1999) which gives a basis for flexibility management;
- indication of the role of flexibility in response to the changing working conditions which quite often is an important taboo in engineering design activities (De Neufville 2000; De Neufville 2004);
- flexible problem solving in construction projects (Walker and Shen 2002; Walker and Loosemore 2003) based on learning culture of organization;
- Horman and Thomas (2005) have shown the advantages of application of the buffers by pointing out the reasons for using flexibility under changing conditions of execution;
- Conception of product and process flexibility in semiconductor fabrication facility management (Gil *et al.* 2005) giving some examples of potential flexibility tactics on tactical and operational level;
- application of flexibility in managing construction projects (Olsson 2006) focusing principally on flexibility strategies at the tactical level;
- indication of the need to balance the dynamics of the environment with the dynamics of management on the construction site (Telem *et al.* 2006);
- indication of both external and internal uncertainty factors justifying the application of flexibility (Mayer and Kazakidis 2007) in relation to the mining industry;
- the new approach to uncertainty (and risk) as an element of development (Perminova, Gustafsson, Wikstrom 2008) which requires the management based on 3 key elements: learning from examples and sense-making as enablers of flexibility and quick decision-making in response to the analyzed situation.

The purpose of the proposed method is to limit the impact of interruptions on planning and realization of building processes through introducing multiple variants of realization methods. The methodology assumes the possibility of preparing certain options during the initial stage (planning) that will be ready to use during the realization stage in response to the expected implementation conditions (monitoring).

Potential advantages of utilizing the proposed method include primarily:

- better conformity of process planning and realization,

- lower range of variability of the scheduled costs and completion dates under various scenarios of development conditions,
- reduced vulnerability to building process interruptions (higher reliability),
- lower costs of realization a sequence of building processes,
- possible prevention of losses and benefiting from opportunities arising out of varying realization conditions and monitoring processes in progress.

3. Decision model

The presented purpose of the proposed method is realized through choosing such sequence of controls of the sequence of processes during specific stages (0, 1, 2, ..., i, ..., n) that will lead to minimization of control quality function ϕ in the multiple-step decision process using the following data:

- object description, namely the f function generally described by the following equation:

$$x_{i+1} = f(x_i, u_i, z_i), \tag{1}$$

- initial state x_0,
- set of initial actions a_0 aiming at activation of the flexibility options, jointly determined by the controls in stage 0 (initial stage) – u_0,
- set of flexibility tactics $ft_1, ft_2, ..., ft_l$ describing the conditions for applying flexibility options,
- required final state x^* being the expected ultimate result meaning the condition of the facility upon completion of process realization as specified by the object of contract (or the settlement period within the range of contract execution)
- control horizon n, being the control time determined by the n number of stages during which its quality is evaluated,
- forecast of interruptions z_i' for each stage i,
- control performance indicators: global Q_g and local Q_l.

The problem consists in determining the optimum sequence of decisions within the multiple-step decision process on the basis of selecting a relevant strategy of flexibility application. Because the sequence $u_0^*, u_1^*, ..., u_{n-1}^*$ stands for a schedule of building process implementation in specific consecutive stages, the control may account for step-by-step assessments as well as overall evaluation for the entire duration of execution. From the point of view of occurrence of interruptions (as a key problem for the analyzed flexibility management), it seems reasonable to implement a division into development periods (such as months or seasons – when analyzing weather impact on building processes). Various restrictions are formulated for individual development periods, based on such factors as project advancement analysis, observed impact of the environment, etc. We are analyzing a discrete dynamic object for

$$x_{i+1} = f(x_i, u_i, z_i), \tag{2}$$

where $x_i \in X$ is the state vector, $u_i \in U$ – is the control vector, and $z_i \in Z$ – the interruptions vector. We assume that z_i is the value of random variable Z_i with a density of $f_z(z)$. For given f, x_0, φ and f_z one has to determine the sequence of control decisions $u_0^*, u_1^*, \ldots, u_{n-1}^*$ that will minimize the expected value of the performance factor:

$$(u_0^*, u_1^*, \ldots, u_{n-1}^*) = \arg \min_{u_0, u_1, \ldots, u_{n-1}} \underset{z_0, \ldots, z_{n-1}}{E} \left[\sum_{i=0}^{n-1} \varphi(u_i) \right]. \tag{3}$$

To calculate this formula, due to problems arising out of uncertainty and difficulty in fulfilling the stochastic independence postulate, the best solution would be to simulate operation of the analyzed subsystem in realization of a sequence of processes during individual stages, with the assumption of varying scenarios. From the perspective of the assumed flexibility options in execution of building processes, the above specified plan would be difficult to realize without making decisions in relatively short intervals determined by monitoring and forecasting capacity (using the forecasts for z_i'). The objective of the decision-making during the specific stages is to modify the base production system through application of flexibility tactics corresponding to foreseeable interruptions for minimizing the local performance indicator Q_l:

$$(u_i^*) = \arg \min \mathrm{E}\, [\, \varphi(x_i, u_{i-1})], \tag{4}$$

where $Q_l = \varphi(x_i, u_{i-1}) = \varphi_u(u_{i-1}) - \varphi_x(x_i)$, during each stage (depending on process advancement), which indicates double-criteria problem consisting in minimizing costs and maximizing efficiency, where the purpose function depends on the advancement of the sequence of processes during stage i–1 for the given interruptions forecast z_i' for stage i. The global criterion shall be minimization of overall costs of implementing the strategy with preset final state x^* realized in the course of n stages (expression related to state x_i in the final stage with the assumption of $x_n = x^*$ can also be expressed in terms of costs of penalties for exceeding the contract deadline, and additional costs related to continued development outside the assumed control horizon):

$$Q_g = \sum_{i=1}^{n} \varphi(u_{i-1}) + \sum_{j=n+1}^{m} \varphi(u_{j-1}). \tag{5}$$

The basic problem with the above formulation of the decision-making issue is the availability of required knowledge, sufficient for decision making, and conditions of decision implementation in probabilistic circumstances. Therefore, it would also seem justified to make decisions using simpler models as well.

4. Flexibility management method

We assume that the method is used by a building process contractor focused on gaining competitive advantage through gathering know-how of the selected field of activity (specialization).

The proposed method is based on a general algorithm of proceeding as presented in Fig. 1. The first stage requires setting out the limits of the subsystem in the range of the contractor's specialization. The point is to distinguish a quasi-closed subsystem, whose functioning we are able to modify and assess (this can be, for example, a sequence of processes related to concrete application on a road, or installation of facade). Another important point is to determine the time frame for evaluating operation of the subsystem, which – considering seasonal quality of the building industry – is of key importance for the results of activities undertaken during the next stage, namely specification of major risks and uncertainties. Then, within the range of specific development condition scenario, one should generate different flexibility options (which should primarily mean activities aimed at limiting the impact of interruptions) and associated tactics and strategies. The purpose of the fourth stage is to evaluate the generated variants for various scenarios/cases. If the results are considered satisfactory (at the point

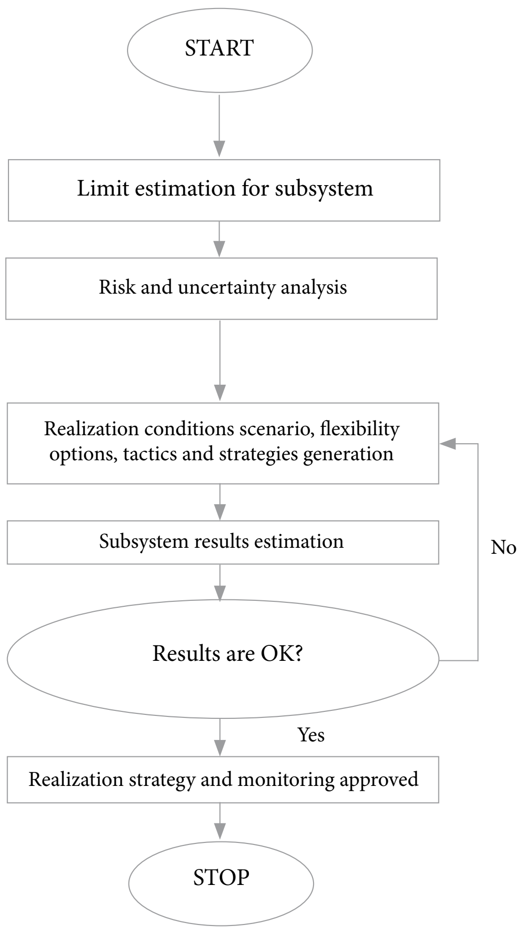

Fig. 1. Flexibility management method idea in planning stage

of contract negotiation), then one should determine approved flexibility strategies (together with corresponding tactics and options) and rules of monitoring. Otherwise, appropriate changes should be made (for instance, new options, tactics or strategies can be generated, etc.). Obviously, if no satisfactory solutions are available, one may also consider possible variation of subsystem operation timeframe (which may lead to changes in key risks and uncertainties), or abandoning implementation of flexibility (assuming a realization strategy without flexibility).

An important aspect of the development stage is monitoring of the environment and processes in progress, enabling selection of flexibility tactics on the basis of comparing advancement of works with the plan (for the current stage) and forecasting development conditions for the next stage. Special attention must be paid to completion of realization of a sequence of processes, which requires preparation of special tactics (such as exceeding maximum achievable daily efficiency through extending the working time or increasing the output of plant and equipment used) in case the processes fail to advance properly and the assumed completion date is at risk. Use of such tactics is determined by the risk of occurrence of additional costs (losses and penalties due to exceeding the agreed completion date of a sequence of processes).

5. Possible applications of the proposed method

The potential applications of the described method were considered with reference to several studied cases: construction of airstrip in summer conditions, installation of a tall building facade, concrete application on highway structures in reduced temperature. The reason for implementing the proposed method is the positive balance of profits and costs arising out of implementation of a flexible approach. Obviously, this depends primarily on the analyzed production system's vulnerability and practical possibility of implementing flexibility options. Assessment of efficiency of flexibility implementation depends to a significant extent on the given development conditions scenario – for very optimistic process conditions, the base solution (no flexibility) can prove better than the use of various flexibility options. In average conditions, however (the NORMAL scenario), one should expect beneficial results of flexibility implementation. This is confirmed by profit distribution analysis for the case of construction of a runway (as an example of a highly weather sensitive process). Limits of the subsystem were determined with primary focus on the concrete application operation (production, transport, laying of concrete mix, concrete maintenance and curing). Because summer conditions were considered, rainfall was taken as the main interrupting factor. The basic flexibility options included possible use of shielding in the form of roofed structures protecting fresh concrete surface against destructive impact of precipitation, and a surface additive accelerating the process of gaining fresh concrete surface resistance to rainfall. Analysis of the comparison of profit distribution in case of executing runway construction processes according to base strategy (no flexibility) and according to a strategy featuring flexibility – H1 (surface modifier), as presented on Fig. 2, shows an advantage of applying flexibility. For the base option, profit distribution concentrates negatively in its lowest ranges.

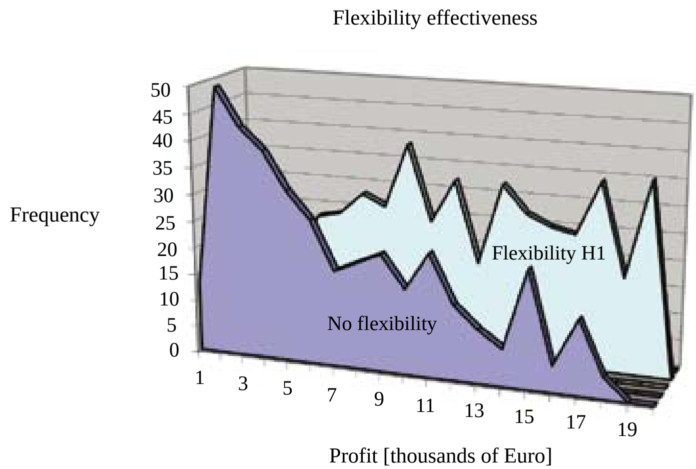

Fig. 2. Flexibility strategy effectiveness – normal scenario – runway concreting example

If flexibility strategy based on single H1 tactics is used, the situation improves greatly – profit is distributed fairly equally, except for the lowest ranges. We should emphasize that the analyzed diagram presents the outcomes of a strategy based on a single tactics, without the added benefit of monitoring effects. Significantly better results should be expected if a combined strategy is used along with regular tracking of process advancement.

6. Conclusions

The generally presented flexibility management method in planning and execution of building processes, with an example, leads to the following conclusions:

1. The presented concept is based on one of the components arising out of specificity of the construction industry, namely the possibility of physically impacting risk and uncertainty on source level.
2. Technological progress in the construction industry and in other fields (such as data collection, transmission and analysis, as well as decision-making support) provides grounds for dynamic development of the proposed approach through expanding opportunities for generating new flexibility options and tactics.
3. Effective and efficient application of flexibility strategies requires certain specific conditions, such as high vulnerability to interruptions, possibility of implementing flexibility options, etc.
4. The proposed method is an attractive alternative for the traditional building process planning that typically assumes a single realization option, which in case of major changes in realization conditions may lead to occurrence of losses (for a negative scenario) or unused opportunities (positive scenario).

The basis for efficient and effective application of flexibility is systematic gathering of knowledge (learning) on the basis of example applications of various flexibility options, tactics and strategies in different conditions. Considering the volume of data required for analyzing effectiveness and efficiency of flexibility tactics and strategies, one should point out the possibility of utilizing a user-friendly advisory system (assuming its permanent implementation on site).

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LANKSTUMAS STATYBOS PROCESO INŽINERIJOJE

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Santrauka

Aplinkos poveikis statybos procesui yra būdingas statybos pramonei nepaisant prevencinių veiksmų (surenkamųjų elementų gamyba, robotizacija). Pasiūlytas metodas buvo sukurtas stebint problemas, atsirandančias vykdant oro sąlygų veikiamus statybos procesus (pavyzdžiui, trikdžius) oro uostų, magistralinių kelių, logistikos centrų, aukštų pastatų fasado įrengimo darbų, statybos aikštelėse. Sukurtojo metodo esmė – pasiūlyti daug variantų konkrečiam procesui įvykdyti. Tai leidžia parinkti tam tikras konkrečių darbų etapų įvykdymo sąlygas. Tyrimas patvirtino, kad šis metodas pranašesnis už tradicinį planavimą, teturintį vienintelį darbų įvykdymo variantą.

Reikšminiai žodžiai: lankstumo valdymas, statybos inžinerija, statybos procesas, planavimas ir stebėsena.

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