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Research Article

The Impact of Failure Types in Construction Production Systems on Economic Risk Assessments in the Bidding Phase

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The aim of the paper is to research and analyze the impact of the type of failure on economic risks in the bidding phase, as the most important part in the management of construction projects. The survey included the impact of risk on the process of determining unit prices from the perspective of a potential contractor. Also, the failure rate and repair rate of the 34 machines from the machine park of the company for road construction were researched. On the basis of obtained parameters and depreciation periods, the operational availability of components of construction production systems was determined. The proposed methodology for estimating impact of the availability function is a modified method of the frequency balancing. It has been tested on a concrete project from the practice in the process of harmonizing construction norms of time that preceded the final adoption of the unit prices. Differences in prices are results of the system failure of construction machinery and plants and have justified a hypothesis of obtaining more realistic costs that can occur in the projects.

1. Introduction

Risk management as the most important part in the project management, in the construction field, is a topic that is the subject of research of a large number of published works. In an integral approach to risk management, from the conceptual projects to the construction phase, significant risks have been analyzed in terms of

(i) Project financiers
(ii) Project investors
(iii) Design companies
(iv) Contractors
(v) Subcontractors (cooperatives and suppliers of equipment and materials)

Although all risks are not equally relevant to all participants in the preparation and implementation of the complex construction projects, it can be adopted as a rule that risk management is consisted by the following stages:

(i) Identification
(ii) Assessment
(iii) Analyzing
(iv) Planning and reduction
(v) Allocation
(vi) Monitoring and updating

Common to all risks, regardless of the category to which they belong, are economic risks. Although there are different approaches to managing economic risks, for all it is valid that they are in the function of the participants in the project, i.e., the type of mutual agreements, the specifics of the projects, and the stage in which the projects are.

Risk management in the preproject phase is a very specific and insufficiently explored area.

This phase of project management is of great importance from the perspective of a potential contractor because it refers to the development of the offer, i.e., calculation of costs and profits within the price of works. Unlike the quantity of works, prices remain unchanged in most cases that could not be claimed for the costs of individual positions and total works.

The specificity of the bill of the quantities (BoQ) as the most important part of an offer is reflected in the complex work on the development of alternative solutions when the structure of unit prices is in question. Research of the market for construction materials and semiproducts, potential cooperatives, and equipment suppliers is a simpler part of inputs in the process of cost and price analysis. This could not be said about the process of reviewing and adapting construction norms of the time for the analyzed project.

The highest number of contracts between the investor and the contractor is based on the unit prices of the positions from the bill of the quantities. The total value of the works carried out in such situations may *deviate* from the contract in the case of variations in quantities and *unexpected* and additional works. This may represent the investor's risk from the point of view of the total cost estimates on the project. For the contractor in such situations, the risks are minimized if the unit price structure contains adequate time norms for construction machinery and plants with associated manpower.

Based on the research of literature and bills of quantities in the field of road infrastructure, where highly mechanized work is represented, *variations* in the installed capacities of machines and equipment are observed. The causes of variations are found in the specifics of each project. Also, in the process of *assessing* the actual capacities of machines and plants, it has not been noticed respecting the failure of construction systems. These approaches have resulted in high risks from the point of view of the contractor when it comes to costs and profits on projects. On certain positions of the works, the unit prices were less than the cost and vice versa. Due to the importance of the failures of the components and the system as a whole, the operational availability of 34 units of the machine park of the company was investigated.

By analyzing various risk factors in bidding phases, the lack of determining the availability of construction machinery and equipment has been identified, i.e., the impact of the type of failure on economic risks. This has influenced the selection of the paper's topic choice.

In order to avoid such risks, it is necessary to introduce the availability function, i.e., to respect the *predicted time of failure and repair of construction machines and equipment in the process of determining the norm of time for each of the contracted work positions*. The proposed modified frequency balancing method can be used in the process of determining the real design capacities and costs of the components and construction systems as a whole in the case of the *dependent* and *independent* failures of the components, as well as parts of the system.

2. Literature Preview

Because of the *complexity* of the risk management process, it can be said that it represents the project in the project management stage. Each risk type entails an economic risk that can be expressed in a direct or indirect manner. The number of published papers refers to the risks involved in the development of detailed projects and also the risks in the process of constructing buildings, as discussed by Alfalla-Luque et al. [1].

The importance of recognizing risks in the cost estimation process from the aspect of multicriterion ranking of alternative solutions is a systematic approach and requires well-trained staff based on an experiential approach discussed by Ferrada et al. [2] and McCaffer et al. [3]. Recognizing the needed time and the available budget in order to achieve quality-based standard requirements is also a challenge for experts in this field, described by Smith [4].

Databases and empirical approaches in analyzing the impact of identified risks on costing processes in bidding phases are the subject of research by a large number of scientists and engineers. The emphasis on the skills of the project manager at the project implementation phase may also influence the reduction of risks from several aspects, because the risks in the management of construction projects are the most often assessed on the experience-based judgments. Generally speaking, it can be noted that in the management of risks in the construction industry, there are often unplanned situations with *unknown* and *unforeseen* risk factors, as discussed by Akintoye and Mac Leod [5], King and Neufville [6], and Shash [7].

For projects where estimates are based on unit prices in bill of quantities, which is the most common case on large investment projects, risk management is gaining in importance in the process of determining unit prices for all work positions. These types of contracts have a specific impact on determining an adequate approach of estimating total costs by the contractor. The final value of the performed works in such situations depends on the final quantities that *vary* in all construction projects in relation to the projected ones and cause *variations* in execution times and costs. Such situations are frequent and in function of the quality of a detailed project. Contractors' risks in situations where contracts are based on unit prices and where there are *deviations* in an amount of positions of works from the bill of quantities are minimized, which is not the case for the owner, as described by Akintoye and Fitzgerald [8] and Hyari et al. [9]. For all recognized risks, regardless of the category and the phase of the project to which they belong, it is necessary to predict the *likelihood* of occurrence and the associated costs, which are in the function of the adopted *probability*. The most common simulation methods used in the estimation process of unit cost and price are Monte Carlo, fuzzy logic, Delphi, etc. by Connolly [10].

Proposals can contain parts that relate to lump-sum cost estimates and most often relate to indirect costs that require a different approach to estimation compared to unit ones. Precisely defined work positions in such cases facilitate the process of calculating indirect costs, as opposed to indirect costs contained in *unit cost structures* that include overheads at the project and company level, as described by Brunes and Mandell [11].

Important statistical indicators in the area of market research and experience on previous projects with different funding modes represent unavoidable data in the process of strategy formulation in cost estimation, as discussed by Arditi and Mochtar [12], Dziadosz et al. [13], and Arauzo et al. [14].

The previous mathematical models for assessing the impact of economic risks contain both *iterative procedures*, as described by Bennell et al. [15] whether within the *theory of games*, as discussed by Runeson and Skitmore [16], within the method of analytical hierarchy process, described by Al-Bahar and Mustafa [17], or within building information modelling as discussed by Brook [18] and Chen and Wen [19].

The research of economic risks from the point of view of theory and practice has proven the specifics of each analyzed project, and the obtained results point to the nonsystematic approach in identifying and assessing risks on parts of individual projects from the conceptual solutions to the final bids, as described by Hughes and Laryea [20].

The impact of the construction systems failure as a very important criterion in the assessment of economic risks in the bidding phase is stated in a smaller number of investigated literature but *without the proposed methodologies for quantifying them*, as described by Ashley et al. [21] and ANSI/PMI 99-001-2017 [22]. Berends et al. [23] stressed that historical bid-based, cost-based, and risk-based are some of the techniques used while preparing final estimates.

Not accepting theoretical achievements in the field of risk management is a common occurrence for the potential contractors. Also, use of the checklists with risk factors and reliance on experience and existing databases is noted by Hughes and Laryea [24]. It can also be noted that *all risk factors for consequences have a risk of an economic nature* and, without respecting a systematic and professional approach in risk assessments in determining unit prices and costs, may result in a *serious failure* by the contractor.

For construction projects in the field of road infrastructure, the most common are contracts based on unit prices. Reduction in the impact of risk on economic indicators in the mentioned types of contractual relations between the investor and the contractor comes to the fore at the level of a detailed project. Namely, the level of accuracy of the quantity of works from the bill of quantities directly affects the risks related to the costs of each position of the works. The practical experience of the research projects showed differences in the contracted and actually executed works up to 3%, while in earthworks there are differences of up to 20%. The largest number of article in the area of the risk in *capital investment* includes systems failures on project realization as factors that affect economic risks in the bidding phase, as discussed by Harper et al. [25].

Integrated approaches in the assessment of economic risks provide a clearer picture of the particular risks that may arise at certain stages of the cost estimate as stressed by Sebestyen and Toth [26]. Also, research on a number of projects has enabled the formation of adequate mathematical models for ranking variant solutions in assessing the *intensity of economic risks*, as described by Pingfeng et al. [27].

Baloi and Price [28] investigated the application of the fuzzy set theory to modelling, estimating, and managing global risk factors in the construction. The possibility of applying the case-based reasoning method to construction projects was emphasized by Radziejowska and Zima [29].

Methods based on fuzzy sets logic were also applied in life cycle cost analysis for completed construction projects by Plebankiewicz et al. [30, 31].

Prašćević published the most important articles of the reliability and availability influence on the performance of the construction machines using the method of frequency balancing, genetic algorithms, and triangular fuzzy numbers [32–34]. Juang et al. [35] describe system availability as an important subject in the design field of production systems that belong to a series-parallel structure.

Part of the researched literature also refers to contracts with fixed quantities of works, besides fixed unit prices. Such cases are very rare in practice, especially in infrastructure projects. In such situations, the contractor may require changes in the contractual relationship, proving the difference in the technical description of the works from the bill of quantities with the actual on site. In this contractual relationship, the proposed methodology remains applicable in the process of redefining quantities, capacities, and economic risks, as discussed by Hyari et al. [9].

The research involved various risks factors in the bidding phase from the point of view of the contractor, as recognized by Jacob and Muler [36]:

(i) Failure of the design concept
(ii) Changes of operator-side requirements
(iii) Failure to implement design concept
(iv) Incorrect calculation
(v) Incorrect scheduling
(vi) Unforeseen soil conditions
(vii) Access to construction site delayed
(viii) Site protection issues
(ix) Responsibility for workplace safety
(x) Third-party demands
(xi) Requirement of additional compensation

(xii) Claim of prolonged construction time
(xiii) Force majeure
(xiv) General changes of legal framework
(xv) Changes in taxation
(xvi) Running costs
(xvii) Repairs after damage
(xviii) Maintenance more expensive than expected
(xix) Insurance
(xx) Law changes
(xxi) Availability/provision
(xxii) Change in technology
(xxiii) Rising interest rates
(xxiv) Inflation
(xxv) Changing in taxation

The abovementioned risk factors indicate the *complexity* of the selected topic of article and further research of impacting various risks factors in cost estimation and determining unit costs in the bidding phase. Mentioned risks factors point to the importance of recognizing the impact of failure types in the construction production system on economic risk management.

As well as in other researched and published works and standards in this field, there are no proposed methodologies for harmonizing the capacities of system components and for the system as a whole from an aspect of failure, i.e., availability function, as recognized by Praščević [32–34], and Mirković [37, 38].

Also, the analysis of published works has confirmed that there is a general approach in determining the value of unit costs and prices ($\mathrm{pr}J_{\mathrm{ps}}$) in the bidding process; i.e., they are in the function of the cost of the system components ($\mathrm{pr}C_{\mathrm{s}}$) and the time norms ($N_{\mathrm{s}}$) that are inversely proportional to the capacities (Q_{s}). The general expression for the unit price of the position of the works ($\mathrm{pr}J_{\mathrm{ps}}$) according to (1), as described by Mirković [37], is

$${}_{\mathrm{pr}}J_{\mathrm{ps}} = \frac{{}_{\mathrm{pr}}C_{\mathrm{s}}}{Q_{\mathrm{s}}} \quad \left[\frac{\$}{m^1}, \frac{\$}{m^2}, \frac{\$}{m^3}, \frac{\$}{t}\right], \tag{1}$$

where

${}_{\mathrm{pr}}C_{\mathrm{s}}$—price of the construction system for realization of the position of the works

Q_{s}—capacity of the construction system for realization of the position of the works

m^1—unit of measure, meters by length

m^2—unit of measure, square meters

m^3—unit of measure, cubic meters

t—unit of measure, tons

The system capacity is inversely proportional to the building norms of time (N_{s}), i.e., according to

$$Q_{\mathrm{s}} = \frac{1}{N_{\mathrm{s}}}. \tag{2}$$

For values of systems' capacity and price, the intervals in which these values can be found are determined. This procedure is called harmonization of building norms, and it is necessary to perform it for each construction project. By introducing the availability function through the failure rate (λ) and the repair rate (μ), it imposes the need to extend the harmonization of the time norms. System costs in order to obtain more realistic values of the unit costs and the price of the position of the works from the bill of quantity significantly reduce the economic risks in the bidding phase [37, 38].

The Association of German Engineers (VDI) recognized the importance of technical availability and published the standard VDI 3423 entitled "Technical Availability of Machines and Production Lines." This standard contains terms and definitions, determination of time periods, and calculation [39].

According to the theory of systems analysis, researched papers, and practical experiences, construction production systems are serial-parallel structures with the following types of connections [40, 41]:

(i) Serial
(ii) Parallel redundant
(iii) Active parallel k/n (hot reserve)
(iv) Passive parallel k/n (cold reserve)

The rule that the failures of serial connected subsystems or components affect the system failure, i.e., that the failures are dependent, in the systems of construction machines and plants is conditional. This attitude is a consequence of the research of all the positions of the works from the bill of quantities, as one of the most important parts of the tender documents. Namely, after the failure of serial connected components or subsystems, other parts of the system can function smoothly or for a certain period, all in the function of the technological process and the type of materials and raw materials that are used.

The significance of availability from the aspect of maintenance of production systems (ACM) in relation to maintenance based on reliability (RCM) is emphasized by Ceschini and Saccardi [42]. Also, the availability of production systems in the function of reliability and maintainability, from the aspect of an integral approach in the management of industrial plants, is recognized by Lamb [43]. Repairable systems and availability as a part of reliability engineering were discussed by Lazzaroni et al. [44]. Models, statistical methods, and application in theory of system reliability are described by Rausand and Hoylad

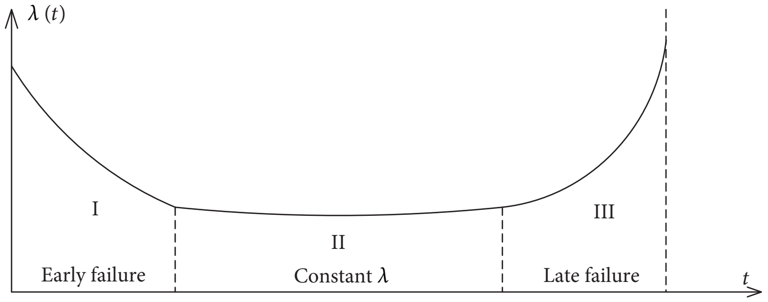

Figure 1: Failure rate in function of depreciation period.

[45]. Also, statistical methods for the reliability of repairable systems, which are applicable to the construction production systems (maintained systems) with analysis of data from single and multiple repairable systems, are described by Rigdon and Basu [46]. Lee and Lim [47] have investigated the intensities of damages to construction projects caused by workforce and machine failures in the function of the work environment and project management. These failures and damages also belong to the factors of economic risks. The importance of applying reliability and availability in engineering design is described by Stapelberg [48].

3. Methodology

The general equation for the availability (A) of components, subsystems, and systems as a whole, according to (3), is

$$A = \frac{\text{uptime}}{(\text{uptime} + \text{downtime})}. \tag{3}$$

Due to the specificity of construction production systems with highly represented machine work and the lengths of time intervals in which they occur, the previous works have proved the stationary in their work, i.e., functioning in *steady state mode*. With maintained systems based on the optimal maintenance policies and availability, an unanticipated number of failures at the business (calendar) year level were detected in order to determine the approximate statistical distribution of the failure and repair time. Based on the survey of the mentioned time for the units of the construction machinery park, the number of failures and repairs was in interval from 4 to 11 at the business year level. Among other things, such results indicated the necessity of introducing the *operational availability function* and *depreciation periods* in assessing the availability of construction machinery and equipment in the process of predicting economic risks in the bidding phase.

Namely, with respect to intensity of the failure (λ) in the function of time (t), i.e., the function of reliability and availability in the function of the depreciation period of components and systems, according to Figure 1, there are three characteristic periods in the life cycle of systems and components.

The obtained expressions for project operational availability (A_{po}) in function of the age of the system are the result from the long-term research of the machine park units. The same are in the function of the indicated periods (I, II, and III) of Figure 1.

The estimation of project operational availability of components (A_{po_I}) from period I corresponds to

$$A_{\text{po}_\text{I}} = \frac{A_{\text{o,aritmetic mean}} + A_{\text{o,max}}}{2}. \tag{4}$$

The estimation of project operational availability of components from the middle part of the depreciation period (period II) corresponds to

$$A_{\text{po}_\text{II}} = \max \left| A_{\text{o,aritmetic mean}}, A_{\text{o,last year}} \right|. \tag{5}$$

The estimation of project operational availability of components from the last part of the depreciation period (period III) corresponds to

$$A_{\text{po}_\text{III}} = A_{\text{o,last year}}. \tag{6}$$

Input data for the operational availability of the components were obtained from the database based on (7), as described by Stapelberg [48]:

$$A_{\text{o}} = \frac{\text{OT} + \text{ST}}{\text{OT} + \text{ST} + \text{TCM} + \text{TPM} + \text{TALDT}}, \tag{7}$$

where

OT—operational time
ST—standby time
TCM—total corrective maintenance time
TPM—total preventive maintenance time
TALDT—total administrative and logistic time

Equation (7) represents an adequate approach to determining the value of the operational availability of the components due to the respecting of component delays when the cause of the same is not their failure but failure of other parts of the subsystem or the system as a whole (ST).

Belonging to the series-parallel systems, the process of determining system availability of construction production systems was carried out by the reduction of the serial-parallel system to an equivalent serial system where all subsystems are analyzed from the aspect of independent failures, in order to determine the availability in the function of *dependent and independent failures* of the *equivalent* serial system. The acquired capacities, total, and unit costs of the subsystem and the system as a whole are determined for the acquired values of availability. This approach allows obtaining the limit values of the intervals of the mentioned parameters within which unit prices with different risk intensities can be adopted.

The investigated serial-parallel system is consisted of m subsystems and n components (C_{ij}), where $i = 1, 2, \dots, n$, and $j = 1, 2, \dots, m$.

3.1. Assessment of the Availability and Capacity of Subsystems with Parallel Connected Components. The failure of one or more components, in the case of parallel connection, does not have a direct impact on the failures of the remaining components, especially in the case of timely repair or replacement of cancelled ones, which, in construction, can be measured in hours due to specific technological processes. The expression for project availability assessment (A_p) according to (8) [32, 37], is

$$A_\mathrm{p} = 1 - \prod_{i=1}^{n_j} \left[1 - A_{\mathrm{po}_{\mathrm{I,II,III},i}} \right]. \tag{8}$$

Project capacity of subsystem (Q_p) according to (9) [32, 37] is

$$Q_\mathrm{p} = \sum_{i=1}^{n_j} Q_{\mathrm{c}_i} \times A_{\mathrm{po}_{\mathrm{I,II,III},i}}, \tag{9}$$

where

Q_{c_i}—capacities of subsystem components without failure

$A_{\mathrm{po}_{\mathrm{I,II,III},i}}$—project availability of system components according to (4), (5), and (6).

3.2. Assessment of Availability and Capacity of Subsystems with Active Parallel Connection k/n. For the number of redundant components ($n_j - k \geq 1$), the expression for project availability assessment (A_p) according to (10) [32, 37] is

$$A_\mathrm{p} = \sum_{i=k}^{n_j} \binom{n_j}{i} \times A\mathrm{po}_{\mathrm{I,II,III},i}^{\,i} \times \left(1 - A\mathrm{po}_{\mathrm{I,II,III},i}\right)^{n_j - i}. \tag{10}$$

The project capacity of the subsystem (Q_p) according to (11) [32, 37] is

$$Q_\mathrm{p} = \sum_{i=k}^{n_j} \binom{n_j}{i} \times i \times A\mathrm{po}_{\mathrm{I,II,III},i}^{\,i} \times \left(1 - A\mathrm{po}_{\mathrm{I,II,III},i}\right)^{n_j - i} \times Q_{\mathrm{c}_i}. \tag{11}$$

3.3. Assessment of the Availability and Capacity of Subsystems with Passive Parallel Connection k/n. For the number of redundant components ($n_j - k \geq 1$), the expression for project availability assessment (A_p) according to (12) [32, 37] is

$$A_\mathrm{p} = \sum_{i=0}^{n_{j-k}} p_{\mathrm{I,II,III},i}, \tag{12}$$

where the probability of component failure ($p_{\mathrm{I,II,III},i}$) according to Eq. (13) is

$$p_{I,II,III,i} = \alpha_i \times p_0. \tag{13}$$

The probability that no component has failed, according to the (14), is

$$p_0 = \frac{1}{1 + \sum_{i=1}^{n_j} \alpha_i}. \tag{14}$$

Coefficients α_i according to (15) and (16) are

$$\alpha_i = \frac{1}{i!} \times \left(k \times \frac{\lambda_\mathrm{c}}{\mu_\mathrm{c}} \right)^i, \quad i = 1, 2, \dots, n - k + 1, \tag{15}$$

$$\alpha_i = \left(\frac{\lambda_\mathrm{c}}{\mu_\mathrm{c}} \right)^i \times \frac{k^{(n-k+1)} \times (k-1) \times (k-2) \times \cdots \times (k - l + 1)}{i!}, \quad i = n - k + l, \; l = 2, 3, \dots, k, \tag{16}$$

where

λ_c—failure rate of components

μ_c—repair rate of components

The project capacity of the subsystem (Q_p) according to (17) [32, 37] is

$$Q_\mathrm{p} = k \times Q_{\mathrm{c}_i} \times A_\mathrm{p}, \quad i = 1, 2, \dots, k. \tag{17}$$

3.4. Assessment of System Availability and Capacity with Serial Component Connection. The final step in assessing the availability and capacity of the system is the assessment of serial connected equivalent and individual components (subsystems) in the case of independent and dependent failures.

Independent Failures. For system availability (A) with serial (regular) connection of components in case of independent failures, (18), as discussed by Mirković [37], can be accepted:

$$A=\prod_{i=1}^{m} A_{\mathrm{p}_i}, \quad i=1,2,\ldots,m, \tag{18}$$

where

A_{p_i}—project availability of equivalent and individual system components by (8), (10), and (12).

Dependent Failures. In the case of dependent failure, (19), as described by Prašćević and Trbojević [32] and Mirković [37], can be accepted:

$$A=\frac{1}{\left(1+\rho_1+\rho_2+\cdots+\rho_m\right)}, \tag{19}$$

where

$$\rho_i=\frac{\lambda_i}{\mu_i}, \quad i=1,2,\ldots,m. \tag{20}$$

λ_i—equivalent or individual failure rate of component

μ_i—equivalent or individual repair rate of component

In the serial connection of the components in the case of dependent and independent failures, the capacity is equal to the product of the minimum capacity among all in the series and the availability of the system, i.e., according to (21), as stressed by Mirković [37].

$$Q={}_{\min}Q_{\mathrm{p}}\times A. \tag{21}$$

3.5. Assessment of the Total Project Costs. For the estimation of the total cost of construction production systems for the realization of individual positions of works from the bill of quantities (C_{s}), the (22), as described by Mirković [37], can be accepted:

$$\begin{aligned} C_{\mathrm{s}} &= {}_{\mathrm{pr}}C_{\mathrm{s}}\times A+(1-A)\times C_{\mathrm{ST}} \\ &\quad + {}_{\mathrm{pr}}C_{\mathrm{s}}\times\frac{(1-A)}{A}+D_{\mathrm{extra}}\times P(\%)\times\frac{{}_{\mathrm{pr}}C_{\mathrm{s}}}{100}, \end{aligned} \tag{22}$$

where

${}_{\mathrm{pr}}C_{\mathrm{s}}$—total cost of the system for the position of the works without respecting the failures

C_{ST}—systems costs of the nonoperational stage

D_{extra}—additional days of system operation due to exceeding the construction deadline

$P(\%)$—percentage of costs per day of the exceeded construction period

A—availability of the system according to (18) and (19)

3.6. Assessment of the Total Unit Costs. The basic equation ((1)) for estimating unit costs, by introducing the availability function, takes the form of (23) in the case of dependent and independent failures, as stressed by Mirković [38]:

$$J_{\mathrm{ps}}=\frac{C_{\mathrm{s}}}{Q}. \tag{23}$$

3.7. Assessment of the Total Time Required for the Realization of the Position of the Works. The planned number of hours for the functioning of the system for realization of the position of works (${}_{\mathrm{pr}}h$) are determined [37] is

$${}_{\mathrm{pr}}h=\frac{Q_{\mathrm{w}}}{Q_{\mathrm{s}}}, \tag{24}$$

where

Q_{w}—quantity of the position of works from the bill of quantities

Q_{s}—planned capacity of the construction system for realization of the position of the works

By introducing the availability function, the same takes shape (h) according to

$$h={}_{\mathrm{pr}}h\times A+{}_{\mathrm{pr}}h\times(1-A)+{}_{\mathrm{pr}}h\times\frac{(1-A)}{A}. \tag{25}$$

According to (24) and (25) and the adopted hours of system operation per day (h_{d}), (26) can be determined for additional days of work (D_{extra}):

$$D_{\mathrm{extra}}=\frac{h-{}_{\mathrm{pr}}h}{h_{\mathrm{d}}}. \tag{26}$$

3.8. Assessment of the Contracted Value of the Position of the Works. The contractual value of the position of the works by considering the availability function (C) according to (23) and (24) is determined by

$$C=Q_{\mathrm{w}}\times J_{\mathrm{ps}}. \tag{27}$$

3.9. Block Diagram/Procedure of Methodology. Figure 2 shows the block diagram/procedure of the proposed methodology.

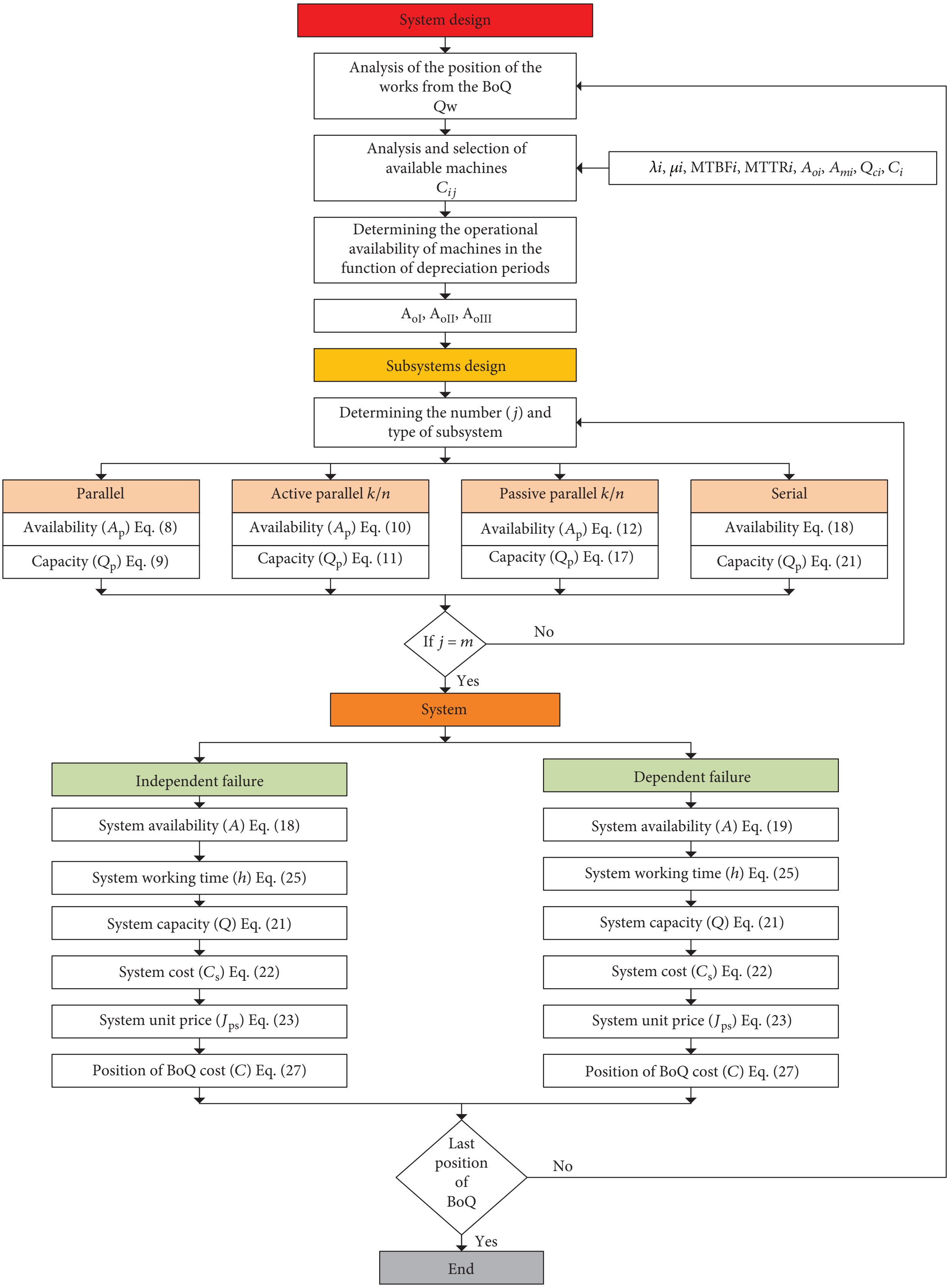

FIGURE 2: Block diagram/procedure of the proposed methodology.

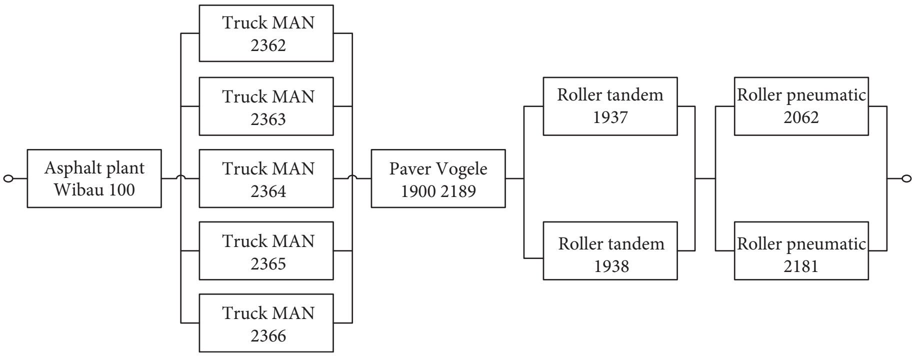

FIGURE 3: System for production and embedding of bitumen-bounded materials.

TABLE 1: Availability and capacity of subsystems.

No.	Subsystem	Period	A_p	Q_p (t/h)
1	1	II	0.9555	95.55
2	2	I–II	0.9999	98.60
3	3	II	0.9737	97.37
4	4	III	0.9997	98.18
5	5	III	0.9998	98.65

4. Methodology Testing

The proposed methodology for estimating the impact of the failure types of construction production systems on economic risks assessment in the bidding phase is tested on the system for production and embedding of bitumen bounded materials. The analyzed system is a consequence of techno-economic optimization in the process of choosing the solution for the position of the construction of the base course of the pavement structure from the bill of quantities. The selection process included all necessary actions in relation to costs and harmonization of building norms, but without the impact of potential system failures.

On the selected practical system, an analysis of the impact of the availability function on actual capacities and economic risks in the choice of components and systems as a whole was performed. For the selection and analysis of the system, the data on amortization periods and availability for 34 explored components of the company's machinery park were used. Figure 2 shows the serial parallel system with 11 components (n) and 5 subsystems (m).

Technological processes for the production and embedding of bituminous bonded materials consisted of three parts, i.e., central plant for the production of bituminous bonded materials, transport means for produced materials, and sets for the embedding of materials. Since the embedding set is composed of pavers and compactors with metal and rubber rollers, from the standpoint of the technology of works and the theory of the system, it is divided into three subsystems [40, 41]. So, the projected system consists of five subsystems with *mutually harmonized production capacities* which consequently have the number of components in the subsystems. In practical cases, no subsystems with hot or cold reserve are yet projected, which may result in additional costs and a bad impact on the quality of the works. On the selected example from a practice that belongs to a serial-parallel structure without subsystem redundancy, the proposed method can be tested from the aspect of the influence of the availability of components, subsystems, and the system as a whole. Namely, the system consists of the following subsystems (Figure 3):

(1) Central plant for the production of bituminous bonded materials (asphalt plant), $Q_p = 100t/h$

(2) Five trucks for the transport of bitumen-bound materials, $Q_p = 100t/h$

(3) Paver for laying and precompacting bituminous bonded materials, $Q_p = 100t/h$

(4) Two compactors with metal rollers, $Q_p = 100t/h$

(5) Two compactors with rubber rollers, $Q_p = 100t/h$

Based on the amortization periods (Figure 1) and data on the operational availability, capacity, and proposed methodology ((4), (5) (6), (8), and (9)), Table 1 shows the availability and actual capacities of all subsystems.

Tables 2 and 3 show the estimated values of system availability in the case of dependent and independent failures and their impact on planned and actual economic indicators from the aspect of economic risk, as well as the capacity of the analyzed system ((1), (2), (18), (19), (20), (21), (22), (23), (24), (25), (26), and (27)). The unit costs and the amount of the work position (94,000.00 tons) for the construction of the base course of the roadway indicate the significance of the availability function with regard to the differences in capacities, and the proposals for the total cost values (C).

Differences in unit and total costs by introducing the availability function are shown in Table 3. The difference amounts that are greater than 20% (26.35 and 26.65) indicate the potential risks and losses in certain positions and total works. However, the differences between the value of the availability function (0.9298–0.9310), the unit costs (12.80–12.83), and the total costs (1,203,200.00–1,206,020.00) in the case of dependent and independent failures indicate a sufficiently narrow interval (26.35–26.65) from which the decision-maker should decide for the final value.

The proposed methodology allows after the completion of all works necessary for the finish of the agreed project that

Table 2: Availability, cost, and capacity of the system.

No.	Syst./failures	A	${}_{\text{pr}}C_{\text{s}}$ ($)	C_{s} ($)	Q_{s} (t)	Q (t)	pr^h	h	D_{extra}	P(%)
1	Dependent	0.9310	1013.00	1138.73	100.00	88.96	940.00	1009.67	6.97	5.00
2	Independent	0.9298	1013.00	1140.13	100.00	88.84	940.00	1010.97	7.10	5.00

Table 3: Unit cost, quantity, and planned and real total costs of the system.

No.	pr^Jp ($/t)	J_{ps} ($/$t$)	Q_{w} (t)	C_{p} ($)	C ($)	C/C_{p} (%)
1	10.13	12.80	94,000.00	952,220.00	1,203,200.00	26.35
2	10.13	12.83	94,000.00	952,220.00	1,206,020.00	26.65

the contractor can perform an analysis of the estimated and actual availability and the unit and total costs. The above data within the proposed methodology upgrade the existing database in order to dispose of the real indicators for the projects that follow. In the investigated system, the actual project availability (A) after the project completion was 0.9311.

The paper confirms the assumption of the majority of author negligible differences in dependent and independent failures in construction production systems, which is confirmed by data on availability differences, unit costs, and total costs (Tables 2 and 3). Also, the proposed method justifies the respectability of the availability function in order to eliminate the risk in the biding phase.

5. Conclusion

The harmonization of the average construction norms (capacities) in the process of determining unit costs and prices in the preparation of tenders is a consequence of the specificity that each construction project contains. Classic approaches are still present in the bidding process and are based on the experience of engineers and staff which determine their values.

The advantages of the proposed model in relation to classic approaches based on average building norms are reflected in the introduction of the failure time and repair time of components, subsystems, and the system as a whole through the function of availability. Due to the specificity of the components of building systems that do not require availability 24 hours a day and sufficient time for maintenance, which results in a relatively small number of failures at the level of calendar and business year and the impossibility of determining the approximate statistical distribution, the proposed model can be applied to all construction (project-organized) systems and industrial systems that function for a sufficiently long period of time, i.e., in steady-state conditions. Also, the obtained test results confirmed the importance of respecting the availability function *as one of the economic risk factors* in the bidding phases.

The proposed method cannot be applied to other technical systems where short time function is required.

Future works from the research area should include a multicriterion approach to cost optimization, taking into account the criteria of availability, project execution time, and quality of works. Also, in future papers, it is necessary to pay attention to the selection of appropriate models for minimizing the impact of a large number of different risk factors on potential economic damages.

Appendix

The figures in the appendix represent data of the operational availability of representative building machine samples for the first, second, and third parts of the life cycle (Figure 1). Also, images represent the evidence of the acceptability of (4), (5), and (6), i.e., predicting operational availability in cases where the number of failures is insufficient in order to determine the approximate statistical distribution. Namely, the number of failures, in all 34 units of the mechanical park, ranged from four to eleven annually.

A. Period I—Truck “MAN TGA 33/2365”

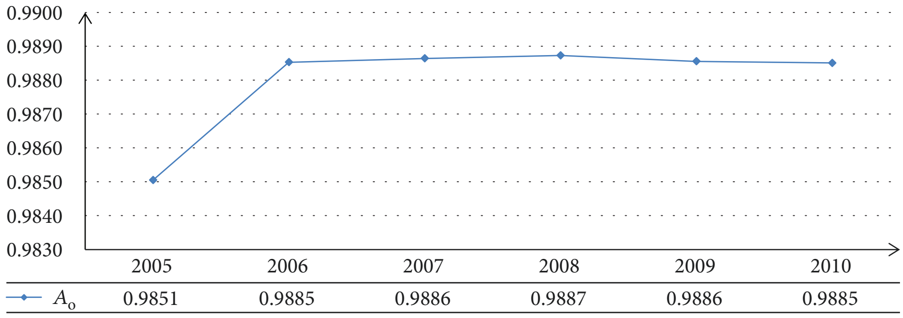

Figure 4: Characteristic form of operational availability function for period I.

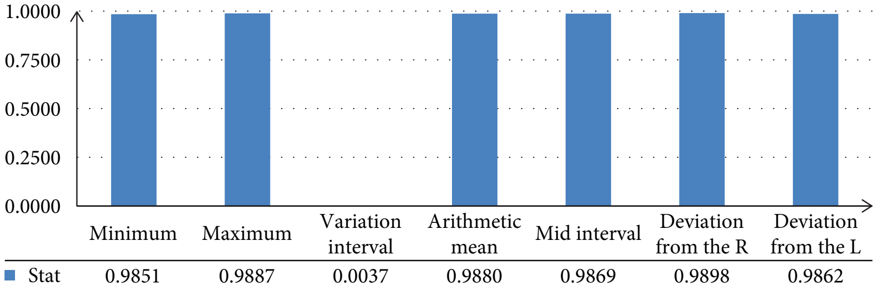

Figure 5: Operational availability statistics for period I.

B. Period II—Asphalt Plant "WIBAU100"

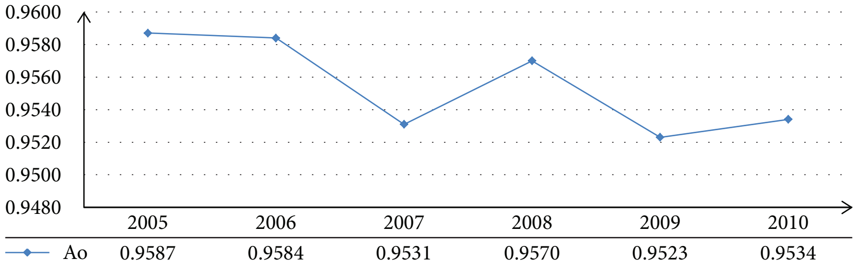

Figure 6: Characteristic form of operational availability function for period II.

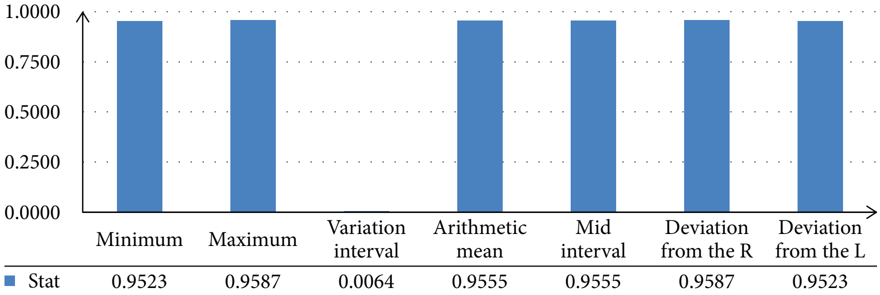

Figure 7: Operational availability statistics for period II.

C. Period III—Truck "KAMAЗ/2115"

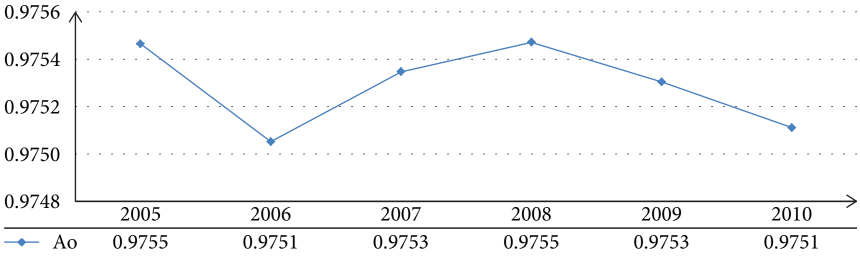

Figure 8: Characteristic form of operational availability function for period III.

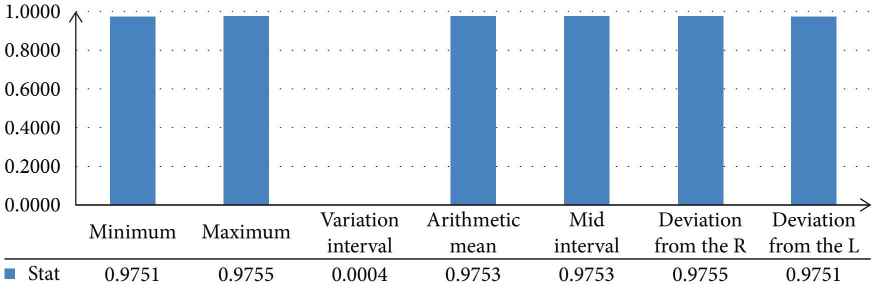

Figure 9: Operational availability statistics for period III.

Data Availability

The survey data were taken from the information system of the company for the reconstruction and construction of road infrastructure. https://data.mendeley.com/datasets/skd3x433n3/1, mirkovic, milan (2018), "Systematized parameters of the availability function and deprecation rate and analysis of the machines availability for research years", Mendeley Data, v1 doi:10.17632/bb5df7zzj8.1

Disclosure

Milan Mirkovic is an expert for road rehabilitation projects financed by international financial institutions. The projects are managed in cooperation with the Faculty of Civil Engineering in Belgrade.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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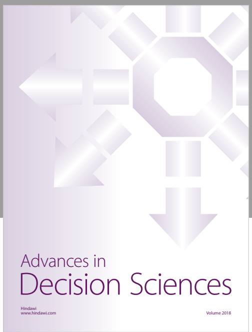
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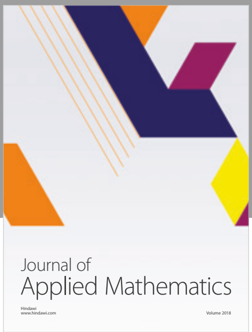
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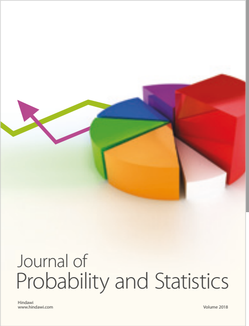
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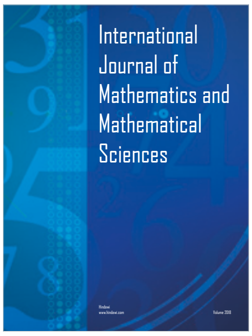
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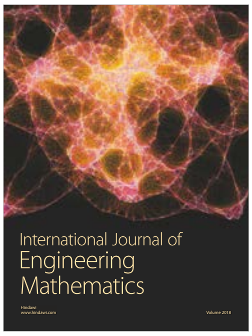
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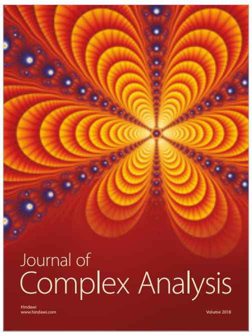
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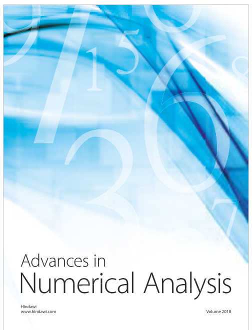
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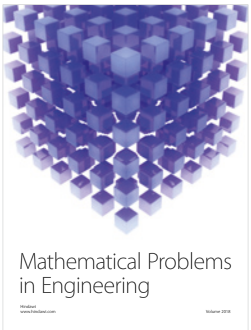
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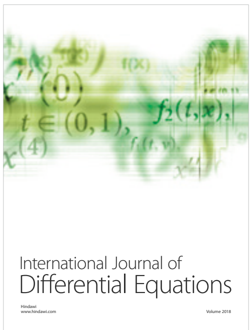
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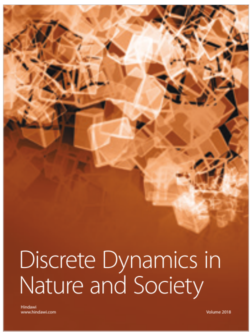
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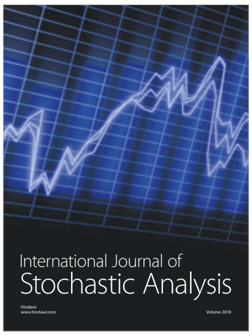
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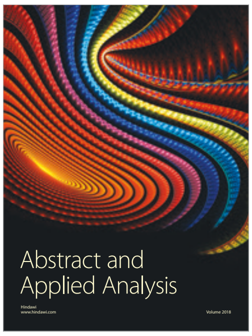
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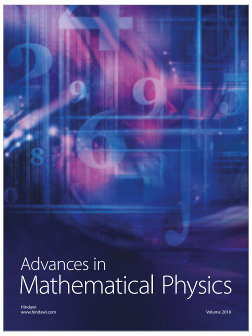
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