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Scenario simulation model for optimized allocation of construction machinery

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Preliminary note

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Optimization methods for narrowing down the choice of resources, and for their allocation, are highly important in all phases of construction projects. This particularly concerns complex project environments where resources (construction machines) have to be allocated to several construction projects at different phases and with different priorities. The authors propose a model based on the multi-criteria optimisation algorithm and the ranking of scenarios involving sub-optimal programs for serial multi-channel operation of construction machines, with a fixed number of machines for final selection, and with separation of the optimum program and/or program scenario cross-sections in complex environment.

Key words:

allocation, binary program, construction machinery, optimization, queues, scenarios

Prethodno priopćenje

Mario Galić, Ivica Završki, Zlata Dolaček-Alduk

Scenarijski simulacijski model za optimalnu alokaciju građevinskih strojeva

Metode optimizacije imaju veliku važnost pri sužavanju izbora resursa na konačni i pri alokaciji resursa u svim fazama projekata. To se naročito odnosi na složena projektna okruženja gdje je potrebno provesti alokaciju resursa (strojeva) na više građevinskih projekata u njihovim raznim fazama i prioritetima. U radu se predlaže model koji se zasniva na algoritmu višekriterijske optimizacije i rangiranja scenarija suboptimalnih programa serijskog višekanalnog rada građevinskih strojeva pri konačnom broju strojeva za izbor, te izlučivanje presjeka optimalnih programa i/ili scenarija programa u složenom okruženju.

Ključne riječi:

alokacija, binarni program, građevinski strojevi, optimizacija, redovi čekanja, scenariji

Vorherige Mitteilung

Mario Galić, Ivica Završki, Zlata Dolaček-Alduk

Szenariobasiertes Simulationsmodell zur optimalen Allokation von Baumaschinen

Optimierungsmethoden spielen bei der engeren Auswahl von Ressourcen, die zu finalen Entscheidungen führt, sowie bei der Allokation in allen Phasen des Projekts eine wichtige Rolle. Insbesondere gilt dies im komplexen Projektumfeld, das eine Allokation von Ressourcen (der Baumaschinen) auf verschiedenen Bauprojekten in unterschiedlichen Phasen und mit unterschiedlichen Prioritäten verlangt. In dieser Arbeit wird ein Modell vorgeschlagen, dass auf dem Algorithmus der Mehrkriterienoptimierung und der Rangierung von Szenarien suboptimaler Programme des mehrkanaliger Serienbetriebs von Baumaschinen bei der finalen verfügbaren Anzahl beruht, sowie die Ausscheidung des Satzes optimaler Programme und/oder Programmszenarien im komplexen Umfeld dargestellt.

Schlüsselwörter:

Allokation, Binärprogramm, Baumaschinen, Optimierung, Warteschlangen, Szenarien

1. Introduction

Decision-making for the final choice or narrowing down the choice of construction machinery applicable for a certain construction work is an everyday problem for site managers, as well as for the company management teams [1]. The dynamic and stochastic environment of construction projects further aggravates the decision making processes and renders them more complex. The complexity is particularly evident in situations when the task is to allocate machines to simultaneous projects that are at various stages of realisation. Relying exclusively on the experience of engineers is often considered acceptable in such situations but, unfortunately, the responsibility which follows this kind of decision-making is also often a subject of subsequent discussions. Quantitative confirmation of such decisions provides a better insight into the problem-solving and decision-making in situations where the solution is not obvious, i.e. when the experience and intuition are not sufficient for choosing between several possible alternatives. [2, 3]. Appropriate modelling and simulation methods and techniques are a logical choice in such situations. However, an isolated optimization of individual projects cannot offer a final optimum solution to an overall problem (involving all projects under consideration) [4]. The constraining impacts the projects have on one another must therefore be considered. In addition, the optimization should provide not only an optimum program (solution), but also all sub-optimum programs (scenarios). These scenarios should be ranked using the predefined criteria (objective functions of the optimization) in order to enable the right-timed intervention for choosing alternative solutions, in case the optimum program fails or the input parameters change considerably. In this way, the planning takes into account the risk of cancellation of the selected program, and allows for flexible planning of individual projects, and the system as a whole. Areas (sections) of satisfactory sub-optimum programs of individual projects, as well as the overlap of sub-optimum programs of all projects, constitute the pool of solutions for further analysis and final decision-making (Figure 1).

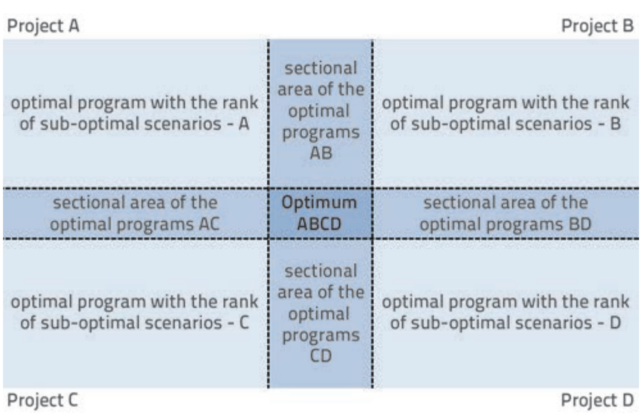

Figure 1. Schematic of an optimum program in a multi-project environment

A methodology for optimum allocation of construction machinery for serial multi-channel operations in a multi-project environment is proposed in the paper. The authors developed their optimization model taking into account the aforementioned assumptions. The model is based on two optimization methods that are commonly used in the domain of operational research, as well as on two objective functions with equal priority:

1. Binary linear programming with evolutionary record of all combinations (scenarios) – the objective function is to ensure minimum total cost of machinery per unit of time.
2. Queueing Theory – the objective function is to ensure maximum usage factor for the most expensive machine in the chain.

The main aim of this research is to set up a model for an optimum allocation of construction machines from a predefined pool of machines used on several simultaneously running projects, with the recording and ranking of sub-optimum scenarios, as a quantitative explanation of the final decision, and to ensure a timely decision-making in case of failure of the selected program. The primary objective of the model is to establish the cross-sectional area of optimum and sub-optimum programs, or to confirm that the cross-section involving all related active projects within the portfolio does not exist. Also, the model has to be suitable for a variety of serial (cyclical) uses of construction machinery, while it should also be flexible in terms of appreciation of changes in project environment.

2. Optimization methods for final selection machinery

In their paper, Rogalska et al. [5] developed and tested the TCM III algorithm (where TCM stands for the Time Coupling Method) by combining the theory of constraints (TOC), critical chain method (CCM), and critical path method (CPM) in the analysis of relationships between the total duration of projects and the costs incurred on such projects. This algorithm has proven to be useful for minimization of labour costs, and for estimation of the total increase of project realisation costs. The authors suggest that this model should be verified on problems of similar nature. The above algorithm is just one among many examples of successful combination of planning and optimization methods on construction projects. Various structural constraints, and relations among various objective functions, are the main generators and motivators for development of new optimization algorithms, and for modification of verified ones. Spatial constraints of construction sites are a typical boundary condition for machine optimization and allocation, as elaborated by Jang et al. [6]. Previous research [7-9] highlights the importance of the optimization evolution recording, with sub-optimum programs as possible alternatives for the optimum program, especially in cases of resource allocation in repetitive operations.

Linear Programming (LP), being the most popular optimization method in engineering circles, is defined by the models involving problems with the linear objective function and structural constraints [10]. Based on the form of optimization variables, the LP is divided into the integer linear programming (ILP), non-integer linear programming (NILP), and their combination known as the mixed-integer linear programming (MILP) [11]. In the domain of ILP, we also have an optimization method for various problems based on inclusion and exclusion of variables (0 and 1), which is known as the binary linear programming (BLP). In BLP, variables are combinations of feasible programs (scenarios). In their review of twenty years of LP use in portfolio optimization, Mansini et al [12] make the following conclusions:

- Variables crucial for decision-making processes have to be expressed in relation to the objective function, and
- Real-time input parameters imply application and necessary simplification of the integer and binary linear programming.

For solving problems of small to medium complexity, Son et al. [13] propose a hybrid optimization ILP model suitable for discrete and quasi-continuous processes, with a single final solution for further planning. The authors also point to the importance of the simplified input of initial parameters and control of the model, through which the model will take into consideration high dynamism of project environment. Bertsimas and Georghiou [14] have developed a mathematical (theoretical) model that transfers the binary decision-making process into the MILP model in the environment where the complexity of the problem increases with an increase in the number of input parameters [14]. This increase and concretisation of input parameters with the realisation of projects is a typical feature of construction projects. It should however be noted that the mentioned model is not intelligible and that it requires modifications through practical use on construction projects. The linearity of the model is a usual theoretical approach aimed at simplifying both the problem and the simulation process, and it is very rarely used in the planning and optimisation of construction projects. This fact is further elaborated by the authors [15, 16] who use non-linear model for cost optimization in terms of pre-contract planning. In their review of achievements and recommendations relating to the optimization of robust problems, Gabrel et al. [17] have reached the following conclusions:

- It is necessary to make an accurate distinction between two types of model sensitivity: feasibility of solutions, and the risk of suboptimality of solutions,
- in case of multi-criteria optimization of robust problems, the use of evolutionary algorithms is recommended, and
- stochastic environment of robust problems is reflected in the changes of input parameters, which implies continuous analysis of relationships between all objective functions [18, 19].

In literature, the optimization of serial cyclic operations is mostly discussed in the domain of the Queueing Theory (QT). The QT is usually defined as a linear (rarely non-linear) program, consisting of one or more phases and channels of servers, which have to serve incoming clients in the time interval shorter than the server operation interval and, as a result, a queue (or queues in case of a multi-channel system) is formed [10, 20-23]. In construction industry, the QTs problems are everyday tasks that usually require, in their simple forms (e.g. one-channel one phased systems, etc.), almost no quantitative confirmation or testing, and are solved based on engineering assessment and experience. However, in case of even a slight increase in the number of channels and/or phases, change of the queue disciplines, or simultaneous demand for the same machines from more locations (construction sites), this problem becomes complex and very risky for an independent engineering decision, unsupported by quantitative data. In such cases, the modelling and simulation methods are a logical tool for problem solving [24-26]. Open type queues with infinite input are not common on construction projects. Systems with determined number of clients on entry, i.e. closed systems (M/M/k type of queues) are more usual, as well as the "first in –first out" (FIFO) queue discipline. Terekhov et al. have developed a model that combines QT with planning the alternating operation of two machines, and have proven that this combination gives the QT method a new dimension in projects planning [27]. However, this model does not offer the evolutionary optimization recommended for robust multiple ongoing systems. Motivated by the constant increase in fuel costs, Stein et al. use a modified QT in which the total fuel consumption is set as an objective function of all related processes (e.g. construction sites, transport, etc.) [28]. By event generation and simulation, Sharma et al. have developed and tested an optimization model and algorithm for allocation of resources (i.e. labour and machines) with one objective function (i.e. minimization of total rental costs) [29]. Their model has proven to be useful for problems with similar one objective function and in case of optimisation of individual projects, without record of sub-optimum scenarios.

Over the past decade, the Neural Networking (NN) has become one of the most popular optimization and event simulation methods in a number of engineering fields. In construction industry, it is mostly used for simulation of events and resources as an alternative or addition to the well-known Monte-Carlo simulation of events [30-35]. Hola and Schabowicz have made NN models for estimating the time and cost of serial operation of soil excavation machines. Their final conclusion is that this method could be even more useful with further improvement and elaboration of machine selection criteria [36]. Similar conclusion is made by authors of paper [37], but with regard to a different spectrum of optimization criteria. The main disadvantage of the NN method, as stated by several authors, and summarized by Kim et al. [38], is the non-transparency of optimization evolution and final decision, as well as the time/effort ratio needed for feedback.

Based on the above literature review, it is clear that previous researchers recommend the following relevant assumptions and requirements to be fulfilled by models for multiple criteria optimization of multiple serial operation of machinery on multiple ongoing projects:

1. model has to acknowledge and be able to cope with the robustness and dynamic environment of the problem,

2. record of all feasible scenarios must be made in terms of evolutionary optimization records, in order to enable definition of sectional area of feasible solutions, and the post-optimum analysis during realization of the project,
3. multi-criteria optimization requires continuous control of relationships between objective functions,
4. simple input and control of input parameters, as well as the export and presentation of results.

3. Multi-criteria optimization model for serial multi-channel operation of construction machines

3.1. Problem formulation

If construction machines from a predefined pool of machines are to be allocated to simultaneous serial multi-channel operations on several ongoing projects, or on the same project but at different locations, and if the pool outnumbers the required machines, and if their characteristics are similar (e.g. efficiency, unit costs, etc.), then the number of feasible combinations exceeds human imagination and experience. In such cases, the modelling and simulation are suitable tools for decision-making. The authors of this paper propose a model and optimization algorithm fully suitable for the aforementioned cases: optimum allocation of machines on simultaneous projects.

3.2. Graphical presentation and concept of the model

The input to the model (shown in Figure 2) is a pool of available machines that can be used for operations on a given construction site. For each project, the first step is the bi-criteria optimization (two objective functions): minimum total cost of serial machine work in a unit of time, and maximum usage factor for the most expensive machine. The optimization is based on BLP with variables being combinations of machine engagement (i.e. 0 - not engaged, 1 - engaged), and it includes an appropriate evolutionary record of all feasible scenarios generated by both criteria. Output data are the optimum program and the ranked sub-optimum program scenarios. By collecting individual optimum programs for each project, a set of feasible scenarios is created for all projects in the portfolio. Therefore, the first important question arises:

Do we have one or several programs that satisfy the section (needs) of all projects?
If the answer is "yes, one" then the next step is the post-optimum (sensitivity) analysis of that program and the final allocation decision. If the answer is "yes, more than one", then these programs have to be ranked according to the mentioned criteria before the post-optimum analysis and final decision. If no program satisfies the needs of all projects, then the second important question arises:

Does any of the programs satisfies the section (needs) of any two or more projects, but not necessarily all projects?
If the answer is "yes", then this program is analysed and the projects included in the section are singled out. The ranking and final selection of these projects is then made, while the projects not included in the section are analysed through their input data, and the priorities can be established, while the final decision can even be based on a single criterion (e.g. time schedule, alternative solutions, etc.).

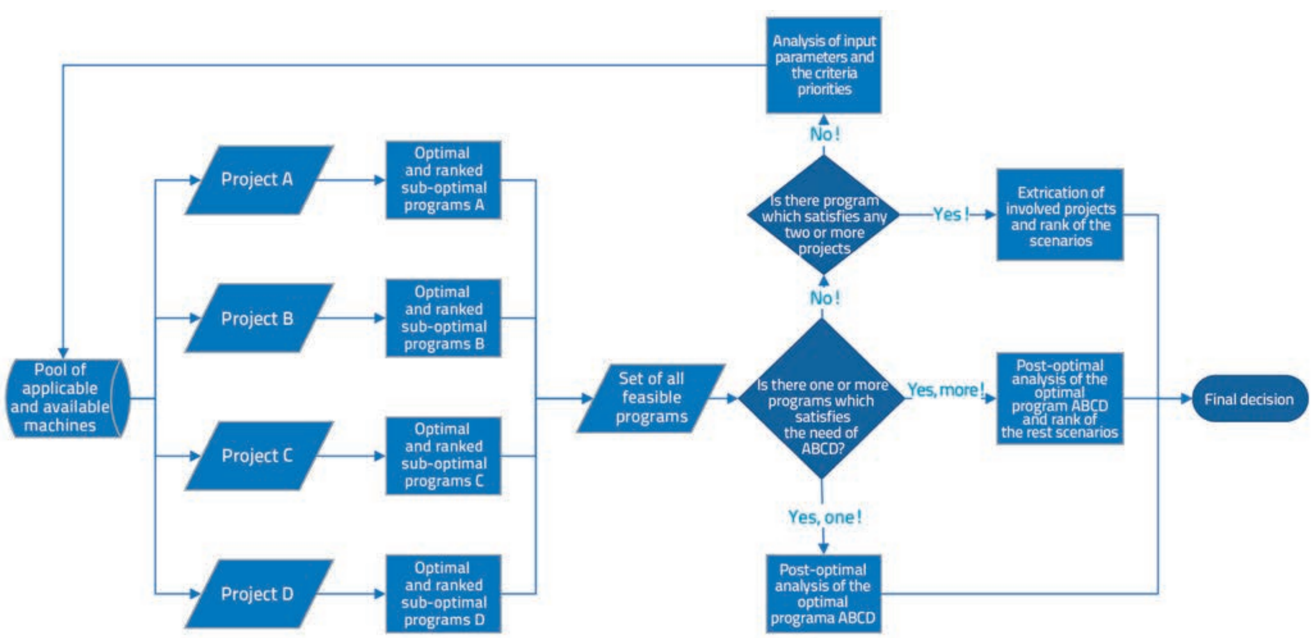

Figure 2. Algorithm of final allocation decision based on multi-criteria optimization

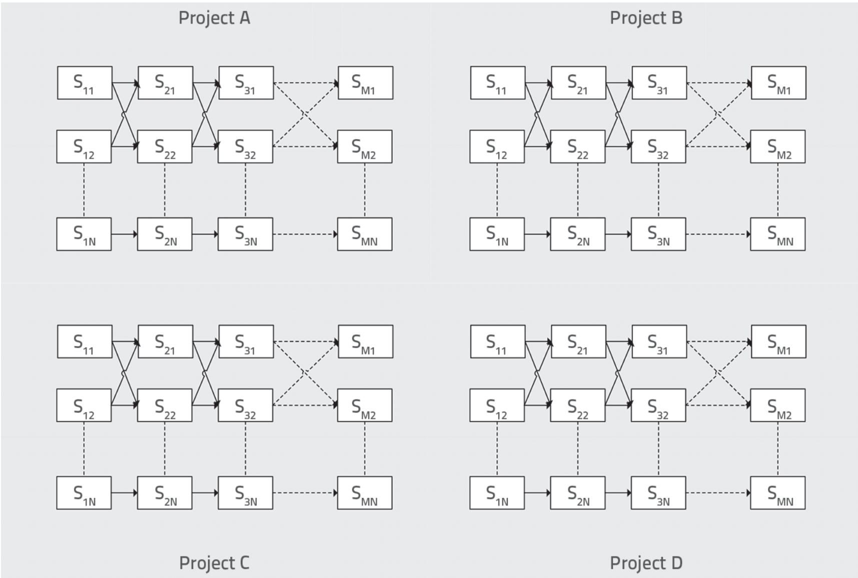

Figure 3. Graphical model of multichannel serial operations in multi-project environment

The multi-channel serial (multi-phase) model of construction machine operations (denoted with "S") is shown in Figure 3. In this figure, "m" denotes the number of phases or various machines in the series, and "n" denotes the number of channels. Full arrows represent the queue discipline (i.e. the first available machine is the first choice – FIFO), while dashed arrows and lines indicate the finality of series and channels. In this phase, the optimization is conducted for each project as if it were excluded from the portfolio.

3.3. Mathematical presentation of the model

The number of projects for which allocation of machines must be made ranges from 2 to "α", while the number of feasible scenario combinations in one project is denoted as "K^{α}", which is dependent on the planned or determined number of machines in the series "m", and is shown in the expression for the number of variations without repetition equation (1):

$$K^{\alpha}(n) = \binom{n}{m} m! \tag{1}$$

$\alpha > 1$; m = 1, 2, 3, ... M; n = 1, 2, 3, ... N

In the set of all combinations, an optimum program has to be singled out and the rest of scenario combinations must be ranked according to the following criteria: total machine costs per unit of time (optimum program is the "minC" in equation 2), and the use of the most expensive machine (optimum program is the "maxρ" in equation 3 given by the general expression in QT defined as a ratio of average entry into the system denoted as "λ" and an average number of serving operations over a time period denoted as "μ"), where the variables "S_{mn}" are binary [0;1].

$$\min C = \sum_{m}^{M} \sum_{n}^{N} S_{mn} \cdot c_{mn} \quad S_{mn} \in [0;1] \tag{2}$$

$$\max \rho_{Smn \to c\max} = \frac{\lambda}{\mu_{Smn \to c\max}} \tag{3}$$

The above mentioned bi-criteria optimization must be made for each project in the environment [2→α] and the rest of feasible scenarios must be ranked. After that, the program section of all project must be found in order to define the programs to be included and those to be excluded. Then the final ranking of machine allocation to projects is made. An optimum program is the one that simultaneously fulfils both criteria in its directions (i.e. minimum total costs and maximum usage of the most expensive machine).

3.4. Simulation model

Based on the mathematical model and algorithm, the authors made a simulation model using the Enterprise Dynamics (ED) simulation software (Figure 4). This simulation software has proven to be a useful tool in simulation of discrete processes in construction industry [24, 39]. It is based on the 4DScript programming language. The model is made of three parts: input parameters, model simulation interface, and optimisation and output data (as shown in Figure 4).

Input parameters – consist of the data and links to external data bases of the suitable and available machines with their characteristics ("Database Connection"), including also the link to the data bases of constructions sites with the GPS coordinates via connection to web servers ("Excel ActiveX"). This approach to input parameter modelling offers connection to predefined (existing) data bases or server data bases (dynamic environment). The aforementioned entities (i.e. "Database connection" and "Excel ActiveX") provide a bypass between external input data and the model.

Model simulation interface – the model consists of all projects in the environment, and features multi-channel serial machine operations with the defined channels and queue discipline, and with appropriate additional data about each project by which machine use is defined (entity "model Documentation"). Each project is defined with a channel input, i.e. frequency of input (entity "Source"), which is actually the symbol "λ" from Equation 3 linked with FIFO connection to the series of servers. The respective correlations are determined by server time distribution ("μ" in Equation 3) and by the output marked with the entity "Sink", which is connected to the entity "Export table" through which individual simulation results are exported.

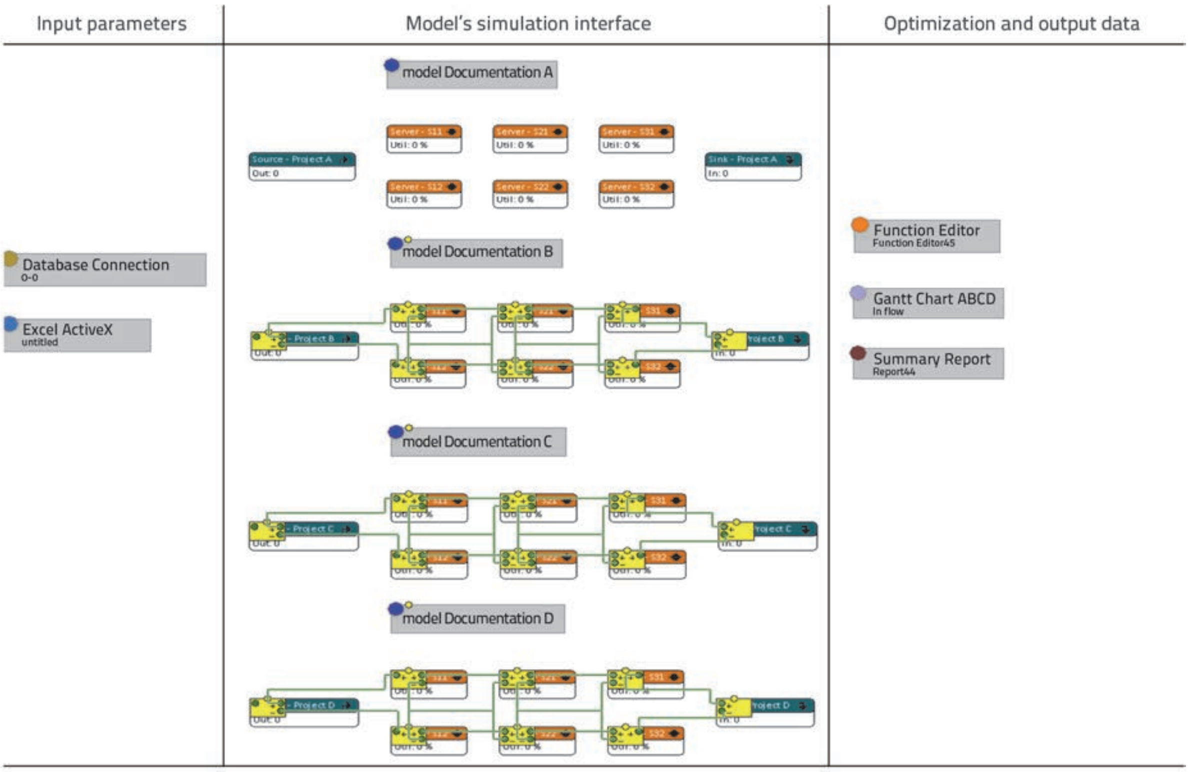

Figure 4. Simulation model for four projects with two channels and series of three machine operation phases, with optimized machine allocation

Optimization and output data – the bi-criterial optimization based on the mathematical model is defined by the entity "Function Editor" or, more accurately, by "atom" in this computer program. As an additional output data, the entity "Gant Chart ABCD" was added for the Gant-chart export for further modelling, as well as the ranked feasible scenarios in matrix form ("Summary Report").

The model shown in Figure 4 is ready for simulation, and it is exclusively controlled through input parameters. The interface of the simulation model is used for simulation setup (i.e. for defining the simulation time and start-up). Output data can be archived in the document with input parameters for further processing and analysis at the project planning and realization phases.

4. Discussion

Previous experience and conclusions in solving robust optimization problems of resource allocation have shown that new methods and models should strive toward simple input of parameters and control of output parameters, and that the evolutionary record of optimisation is important for acknowledging the risk of cancellation or failure of the program that has been selected. Mathematical optimization approaches are used by engineers as a platform for further exploration and modification of existing optimization methods. The existing methods should be explored and sorted according to their applicability for solving specific problems. The model suggested by the authors has proven to be successful in solving problems of fragmented and asymmetric data bases of input parameters in multiple project environments. The model takes into account the dynamism and sensitivity of input parameters. Main advantages of this model are its compatibility and connectivity to external data bases by which the model is controlled, and the evolutionary multiple criteria optimization as a quantitative confirmation for final decision. The main disadvantages are a relatively great effort and time that must be invested, and the basic programming knowledge that is indispensable for development of the model. That is why the model presented in this paper should be further developed in order to simplify entry of input parameters and to ipmprove management of optimisation results. Multiple ongoing projects are common for construction companies, as well as the great dispersion of construction sites belonging to the same project. The authors have developed their model specifically for this type of problems, i.e. for optimisation of robust optimisation problems and machine allocation issues. Multi-channel serial machine operations are common in construction industry, especially in earthworks (e.g. excavation of large foundation pits, and transportation of excavated soil), road excavation and planning works, concrete works (e.g. when concreting great areas at dispersed sites), paving works, etc. Acknowledging the impact of the change of technology is a question that has still remained open in building information modelling (BIM) development. Scenario simulation in technology selection should be expressed as simply as possible, i.e. as a set of additional input parameters for the BIM model and, as such, it is an intersection point of two modelling and simulation concepts (i.e. process simulation and BIM). The simulation of feasible scenarios is one of strong arguments in favour of the BIM concept in all life cycle phases of the project. Thus, output data of the suggested model of the optimum program and sub-optimum scenarios (i.e. Gant-charts) become input parameters for the BIM model. A common feature of both approaches is their object orientation, which makes this link possible, while generation of sub-optimum scenarios is an added value of the connection. Ranked scenarios of feasible programs, and an optimum program guaranteed by the proposed model, will greatly facilitate initial planning and, more importantly, adjustment of plans in the realisation phase of projects.

5. Conclusions

The model proposed in this paper is in an experimental testing and verification phase, and it has so far proven to be a useful tool for an optimized allocation of construction machines on several simultaneous projects. The model is adaptable to changes of input data, it enables comparison of optimum and sub-optimum scenarios with the corresponding output data, and it has thus fulfilled main expectations of the authors. The robustness of the problem does not affect applicability of the model, and the evolutionary record of optimization is ensured. By its nature it is an open source model, which enables control of input data and simulation, and it is ready for connection to external databases. The model consistency and adaptability in resolution of various problems of similar nature should be verified by further research. The model will be tested through finding solutions to various allocation problems. In addition, the concept of the model will further be developed taking into account recommendations made by researches, as well as current IT development trends. In further work, the authors will focus their research on model development and on identification of alternative tools (software) that will enable fulfilment of requirements for commercial use of the model.

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