MODELLING AND SIMULATION OF MONOLITHIC CONSTRUCTION PROCESSES

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Abstract. This research is focused on revealing construction processes from modelling and simulation perspectives. This article reveals the working of the expert system designed and presents analytical capabilities of selected modules. Correct combination of complex production systems of machine sets and group of workers is the main task of the modules activity. The capacity of some modules will be emphasised as far as solution simulations and visualisation of results are concerned. The modules discussed are part of the expert system controlled by users' preferences. Taking into account the specific character of the domain, two kinds of rules have been distinguished (micro and macro rules). Modules SiCE and CoCE exemplify microrules activity, which describe technological and organisational process.

Keywords: construction operations, monolithic construction processes, expert systems, modelling, simulation, visualisation.

1. Introduction

Construction investment process is a long-term and complex activity during which numerous problems occur. A variety of methods and tools are offered by researchers for problems solving at different stages of this process. This article deals with modelling and simulation (M&S) domain. The main goal of the research is to reveal construction processes from modelling and simulation perspectives, where visualization of results is concerned. The paper, on one hand, reveals the working of the expert system designed and, on the other, it presents analytical capabilities of selected modules. This system belongs to a group of tools which provide a new quality in designing construction process by introducing simulation

of modelled processes. Modelling significantly increases the understanding process because relationships between all components of the construction process are exactly formalized. The use of model-based simulation allows to determine the optimal production set of equipment and its detailed analysis.

The expert system presented is concerned with technology designing and monolithic processes organization and is controlled by decision-maker's preferences revealed during a dialogue session.

The expert system designed consists of a data base, knowledge base, inference mechanism, user-friendly interface, and complementary units (modules) such as the procedure for accepting a crane, the module analyzing the work of building gangs, units arranging a set of objects, scheduling module and the unit providing the multi-criterion analysis. Modules serve specific functions in a hierarchically built system. These modules can also work independently, when only partial problems are to be solved.

This paper analyzes a complex cyclic process, discusses the way the process has been modeled and presents simulation results of the working system. For the purpose of this discussion a specific issue has been considered that is the efficiency change of the production set when the construction rises.

The following two modules will be presented in the article:

- Process simulation (SiCE).
- Combination of co-operating machines and groups of workers (CoCE) and visualisation of results obtained in the process of working of these modules.

These modules are named after purpose: Simulation of Co-operating Elements (SiCE) and Combination of Co-operating Elements (CoCE).

The considered expert system architecture is presented in Fig. 1.

Realization of these assumptions, methodological issues, the expert system structure, working of specific modules and application examples were discussed in detail by Hajdasz and Marlewski (1998, 1999), Marlewski and Hajdasz (2000).

Issues of decision support and expert systems in structural engineering domain were discussed in works of Adeli (1988); Brandon *et al.* (1988); Durkin (1994); Anderson (1996); Poon *et al.* (2000, 2003); Poon (2004); Mitkus and Trinkunienė (2006); Kaklauskas *et al.* (2005, 2007a); Zavadskas *et al.* (2006); Golabchi (2008). Expert systems development, classification, methodologies and applications from 1995 to 2004 have been discussed by Liao (2005).

The notion of modelling has been widely researched (Dawood 1994; Yang *et al.* 1996; Aouad *et al.* 2006; Ayers 2007). Researchers have broadly addressed the concept of modelling and employed modelling strategies in various domains of construction, for instance: Yang *et al.* (1996) developed expert systems in construction management; Poon *et al.* (2000, 2003); Poon (2004) introduced a new approach for modelling the construction process based on the use of an expert system; Zhang, Tam (2005) focused on the consideration of break in modelling construction processes; Doloi and Jaafari (2002a, 2002b) designed a dynamic simulation model for strategic decision-making. Problems in modelling, simulation and optimal managing of building processes are under investigation in theoretical and applicable aspects (Kamat and Martinez 2001, 2005; Doloi and Jaafari 2002a, 2002b; Mohamed and AbouRizk 2005; Changwan *et al.* 2006). Advanced simulation and visualization relating to the production processes are discussed by Karhu (2003), Sampaio *et al.* (2005), Kamat and Martinez
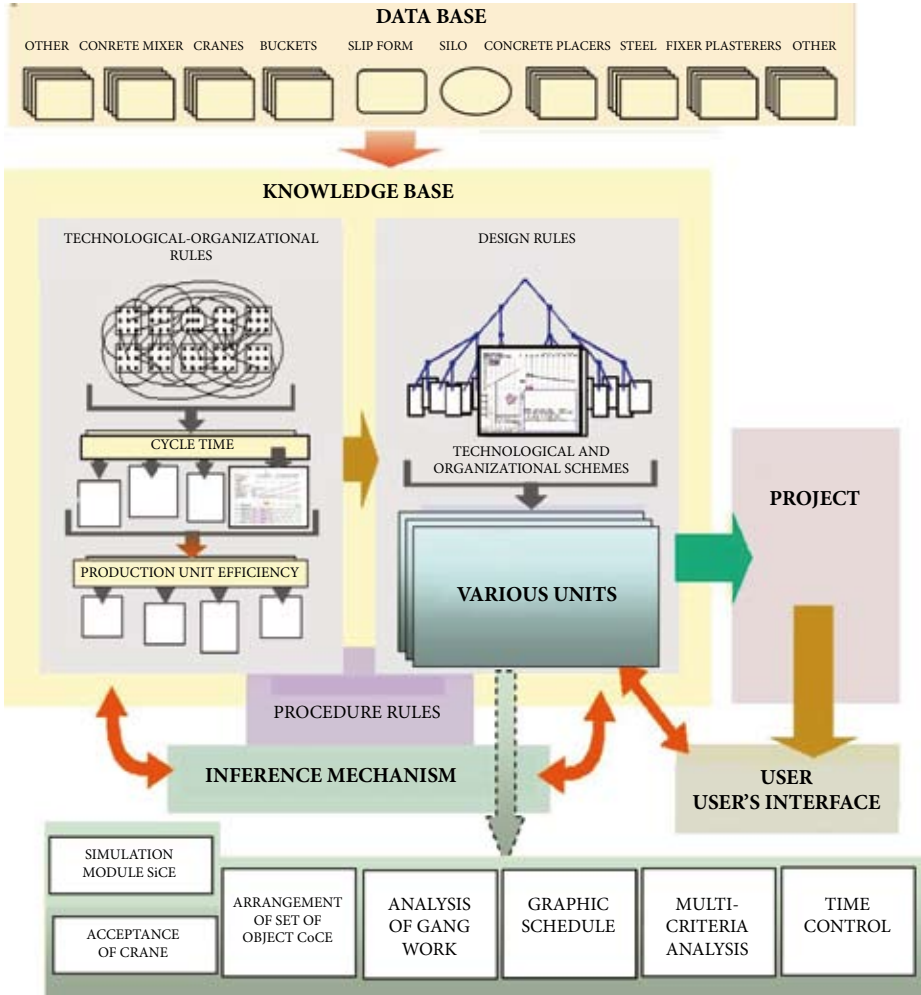
Fig. 1. Expert system architecture

(2005, 2008). Multicriteria decision-making methods have been applied in various aspects of the investment process (Kaklauskas *et al.* 2007a, 2007b; Mitkus and Trinkunienė 2007; Banaitienė *et al.* 2008). For instance, Zavadskas *et al.* (2003) discussed problems of selection of rational construction variants, Zavadskas *et al.* (2008) presented a new method of multiple criteria complex proportional assessment with values determined in intervals – COPRAS-G; Grierson and Khajehpour (2002) presented a computer-based method for the multicriteria conceptual design of high-rise office buildings; Hajdasz and Marlewski (1999) developed multicriteria analysis of the construction process. The author of this paper has consistently continued research on monolithic constructions and linked the study of expert systems and modelling with simulation and visualization of the results obtained.

The expert system and working of selected modules have been further developed by Hajdasz and Marlewski (1998, 1999). This system is constantly under investigation as a generalization of the system for the monolithic construction is yet to be designed (initially the prototype has been developed for the silos construction which has been thoroughly researched by Hajdasz (1998)).

2. Modelling as a design activity

Modelling the construction process has become a popular topic during the last two decades. Since then significant advances have been made in the field of construction process modelling, which is currently subject to scientific research in various building projects. Modeling approach has been applied in construction operations (Kamat and Martinez 2001), construction processes (Poon *et al.* 2000, 2003; Poon 2004) and has been considered as an integral part of architecture practice (Ayres 2007). Recent literature looks on modelling as a design activity and models as complimentary and alternative media, which are often used in research on construction processes (Ayres 2007). One of the greatest difficulties in developing simulation models is an ability to realistically present obtained results. As Ayers points out, the model is distinct from that which has been modelled; however, although distinct, the observer must be able to construct correspondence between features of the model. The correspondence is implying omission of unnecessary details while preserving salient features; therefore, as Ayers notices, "constructing correspondence implies a function for the model and a goal for the observer" (2007: 1226–1227).

This paper concerns a model of a complex system in which features of the process described have been clearly identified and underlined. The main goal was to reveal such features of the modelled in order to analyze the impact on the efficiency of the production set, when the height of the object grows. When the height of the object changes, it affects the conditions of the project realization, which may require modifications of decision-maker's preliminary assumptions, if the initial result is to be achieved. This process has a dynamic nature, which is identified and handled by specific modules.

3. A general model of production system

The problem discussed in this paper consists in choosing right means (machines and groups of workers) in such a way that walls of monolithic silos can be made at a defined speed and in accordance with technological regimes. Also, external factors, concrete curing time, and dynamic character of building process (e.g. an influence of the height of an object built on technological-organisation results) were taken into account. A general model has been presented in Fig. 2.

Objects of the system comprise in this case, among others, slip form, silo batteries, cranes, concrete mixers and groups of workers. The two modules presented concern the above complex cyclic process.

A detailed analysis of the following issues will concern:
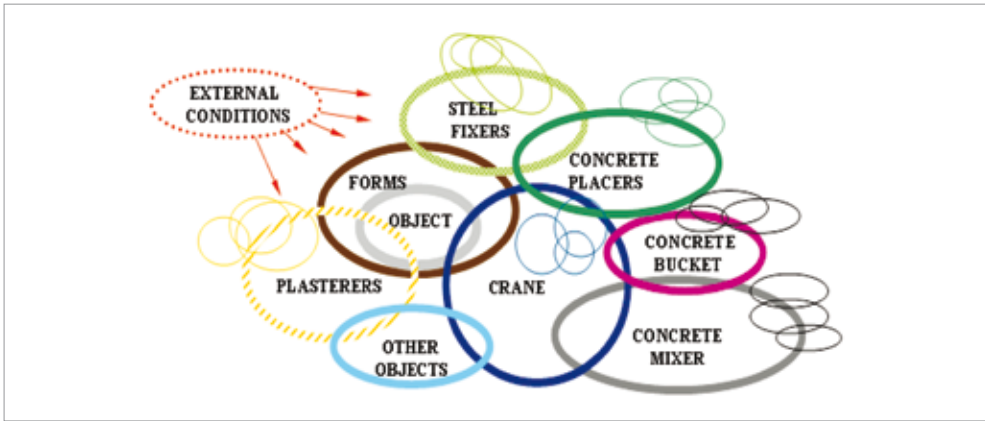
- production: concrete mixers,

Fig. 2. A conceptual model of complexity of cyclical monolithic construction process

AN EXEMPLARY OPERATIONS

CONCRETE MIXER:
1. PRODUCTION OF MIXTURE
2. CONTAINER LOADING
3. WAITING FOR A NEXT CONTAINER

CRANE AND BUCKET:
1. LOADING A CONCRETE MIXTURE
2. TRANSPORTING A LOADED CONTAINER
3. GUIDING A CONTAINER
4. UNGUIDING A CONTAINER
5. TRANSPORTING AN EMPTY CONTAINER
4. CONTAINER LOADING

CONCRETE PLACERS:
1. GUIDING A CONTAINER
2. UNLOADING A CONTAINER
3. SPREADING AND LEVELLING
4. VIBRATING

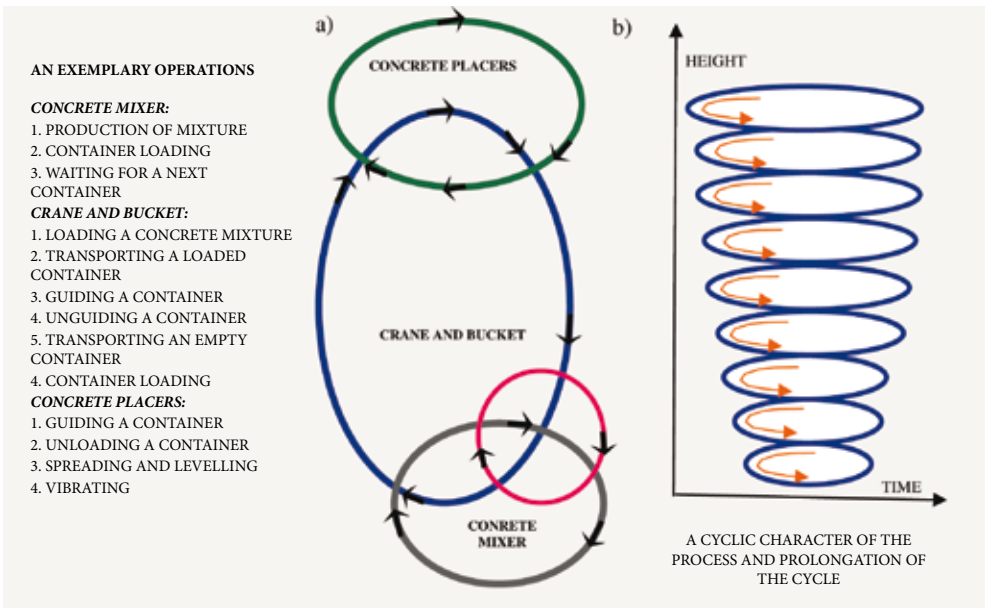A CYCLIC CHARACTER OF THE PROCESS AND PROLONGATION OF THE CYCLE

Fig. 3. A submodel of the construction process

- transport: cranes and buckets,
- concreters' work: concrete placers (4 types of operations are distinguished).

A submodel analyzed in both cases is shown on Fig. 3. A subprocess is presented on Fig. 3a, where activities of a single cycle are also distinguished. A cyclic character of the whole process and prolongation of the cycle when the height of the object grows, is presented in

Fig. 3b (see also Fig. 4). The objective is to select a set of machines and a working group to work in a harmonised way and according to criteria accepted.

This paper discusses cases in which harmonisation of all elements of a system is the key criterion (economic aspects are not taken into consideration). In the first case, a simulation of work of a system comprising one crane, appropriate number of concrete mixers, concrete buckets, and a group of concreters has been presented. Analytical and visualisation capabilities of SiCE module have been presented in detail.

The other example analyses a CoCE module capable of combining sets of a different number of cranes and an appropriate amount of concrete mixers, concrete buckets and concreters in such a way that an uninterrupted work of all components can be ensured. In both cases, a dynamic character of the process has been taken into account.

4. Dynamic process visualisation

SiCE module stimulates a construction process for the above-mentioned objectives (see submodel in Fig. 3) and visualises progress of silos building. Fig. 4 presents a monitor screen illustrating work of SiCE module.

The operation of the SiCE module has to be preceded by a proper selection of cranes, which are to carry out the task. The procedures of selecting the crane have been discussed for the prototype of the system by Hajdasz and Marlewski (1998), Marlewski and Hajdasz (2000), which concerned a non-standard use of a CAS (computer algebra system) applied in this procedure. The issue of a correct selection of cranes has been widely researched and discussed. The expert system for crane selection has been discussed by Warszawski (1990); whereas Lennerts and Kraus (1992) researched ESBE system and Kuo-Liang, Haas (1996) dealt with COPE system for the optimal use of cranes and Ali *et al.* (2005) employed a new approach for automated path planning of cooperative crane manipulators using a genetic algorithm.

The module SiCE operates with the accepted cranes.

The screen presents 3 groups of information for a phase stopped in stroke 668:

- Process visualisation (left-hand side; described below),
- Linear occupancy diagram (bottom part of the screen),
- A file of data and results (right-hand side of the screen).

Linear Occupancy Diagram illustrates changes in a work cycle for each of the 3 main elements, that is, CM (concrete mixers), TB (transporting bucket), CP (concrete placers) in relation to the construction building progress, and their correlation. White rectangles depict work stoppages. For easier observation of particular layers' construction, single cycles have been marked with 2 colours. Fig. 4 illustrates a model of a system which was created with assumption that during the whole process of realisation, production means and working groups will remain unchanged. This means that the bigger part of a building project is accomplished, the less the capacity of a crane and of the whole system becomes. There is also more work stoppage of a concrete mixer and concreters (illustrated by white rectangles).
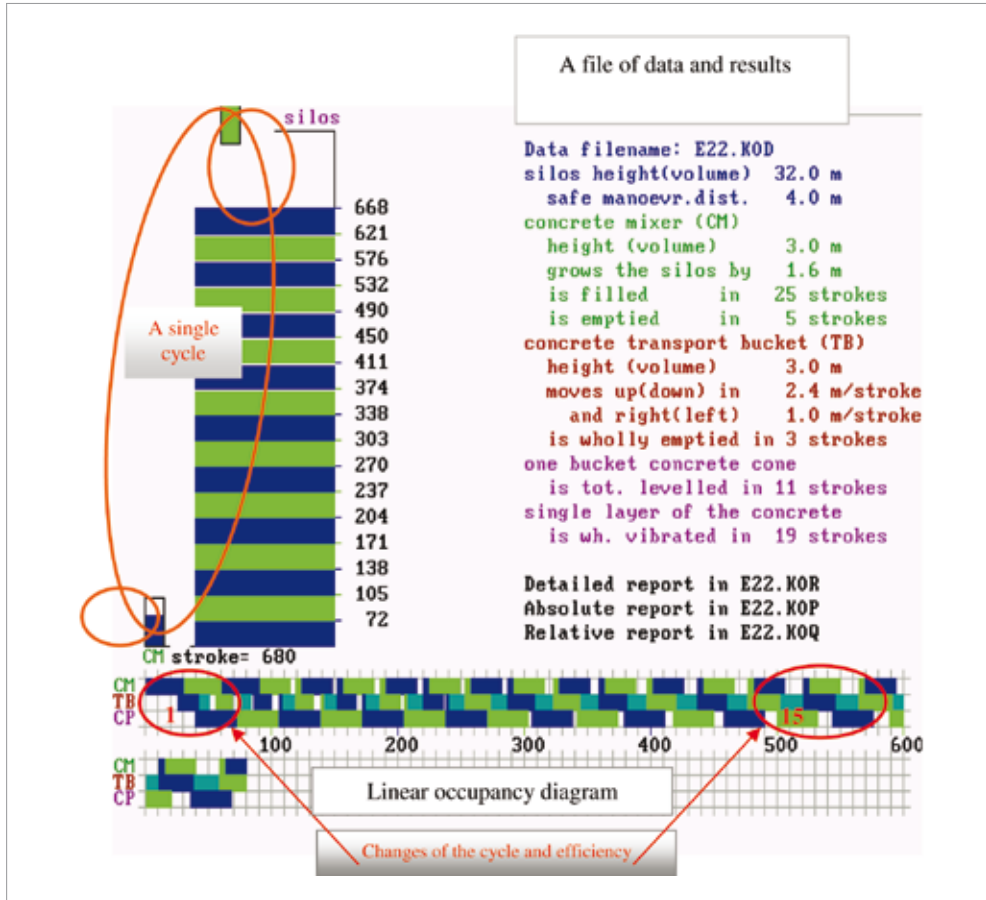
Fig. 4. Full screen produced by SiCE module (simulation captured at stroke number 668)

Considerable differences of the cycle can be distinguished as the cycle 1 is evidently shorter than the cycle 15 (compare with Fig. 3b).

At the same moment, work of 3 main elements of this partial process is being presented. Each of these elements can be in different states:

- States for concrete mixers (CM): production of concrete mix, container loading, waiting for a next container.
- States for a crane transporting a container (TB): loading a concrete mixture, transporting a loaded container, guiding a container, unloading a container, transporting an empty container).
- States for concreters, actions (CP): guiding a container, unloading a container, concrete mixture distribution, vibrating.

Current phases of system work are registered in units, called strokes. A module can work in a constant mode, quick mode and with a mode enabling stopping the strokes. Fig. 5 presents several characteristic phases of the process. It is worth noticing that 3 crucial aspects
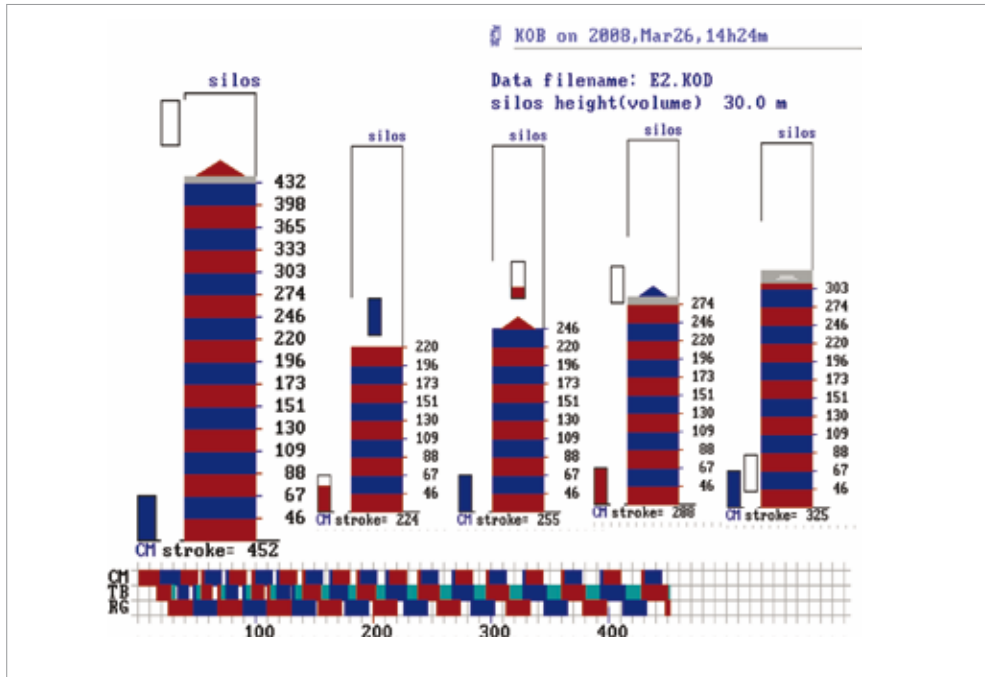
Fig. 5. Dynamic visualisation – 5 characteristic phases of the process

are clearly visible: actions are sequential; they repeat in a technological cycle, some of them are carried out parallel.

When the simulation is completed, the report in a form of diagram is displayed (Fig. 6).

Some data and assumptions are visible on the screen (right-handed side, also Fig. 4) and are registered in detail in result files:

- KOD file reports silos' parameters and data of a concrete mixer, crane, transport container and group of workers,
- KOR file contains summary efficiency of elements interacted, and also progress of construction building,
- KOP file reveals the usage of efficiency in percentages,
- KOQ file reports relative efficiency CM, TB, CP.

Fig. 6 provides graphs with data from these files.

Two examples generated by the module reveal in detail the problem of changing efficiency of the production set discussed in this paper. In both cases the same model of the process has been analyzed, but different parameters of the selected elements have been introduced (the following parameters have been changed: the height of the object, size of buckets, cycle of cranes, and number of workers).
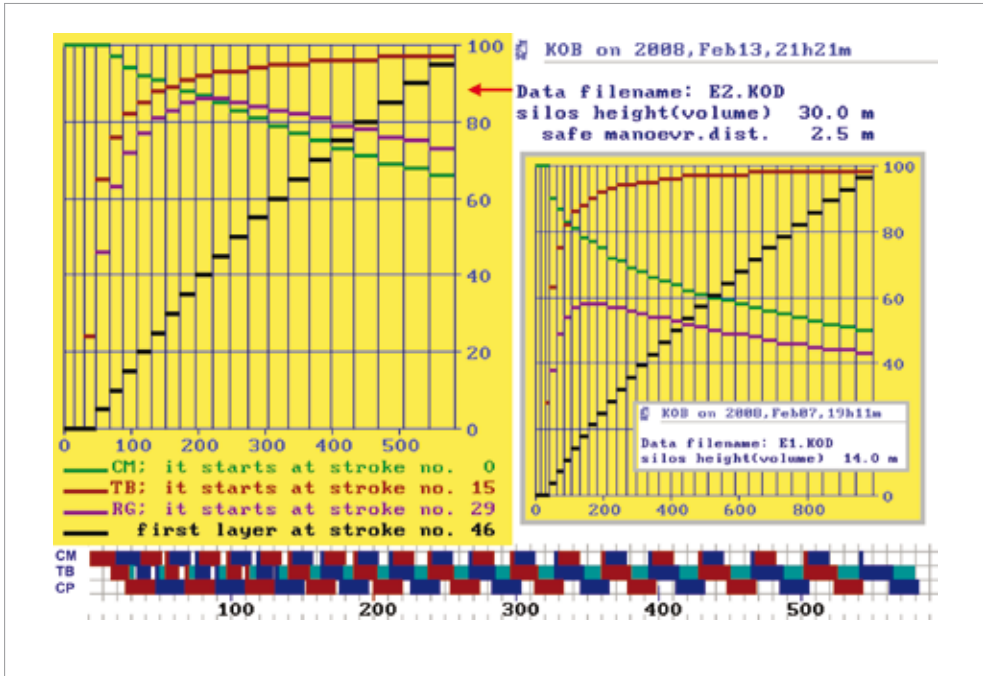
Fig. 6. Percentage of occupancies of elements CM, TB, CP

The diagram shows percentage of absolute and relative occupancies of 3 co-operating elements. Due to different parameters of particular elements, graphs presenting efficiency or cycle lengths have different shapes.

Irrespective of the introduced changes of the parameters, the following tendency can be determined: the efficiency of concrete mixers decreases (CM, green line, decreasing diagram), working of the crane transporting buckets slows down (TB; brown line, the highest graph), the work efficiency of the construction workers decreases (CP; violet line, the lowest graph). Diagrams and results contained in KOD, KOR, KOP and KOQ files, presented in the article, allow for a more advanced analysis as, thanks to this data, it is possible to measure exactly the changes of the efficiency and list the percentage of absolute occupancies of all co-operating elements. As a result of this simulation and visualization of the construction process, relations among all the elements of the system can be distinguished.

5. Combining machine sets and work groups

The above considerations of 3 elements of the set (concrete mixer, crane and buckets, crew) have been presented on the basis of the working of one crane (SiCE module). Inconveniences, related with decreasing efficiency of the production set, when the height of the object grows, can be eliminated by increasing production resources in specific production sets. The working, operations and simulation of the module, when a few cranes are applied, will be discussed below.
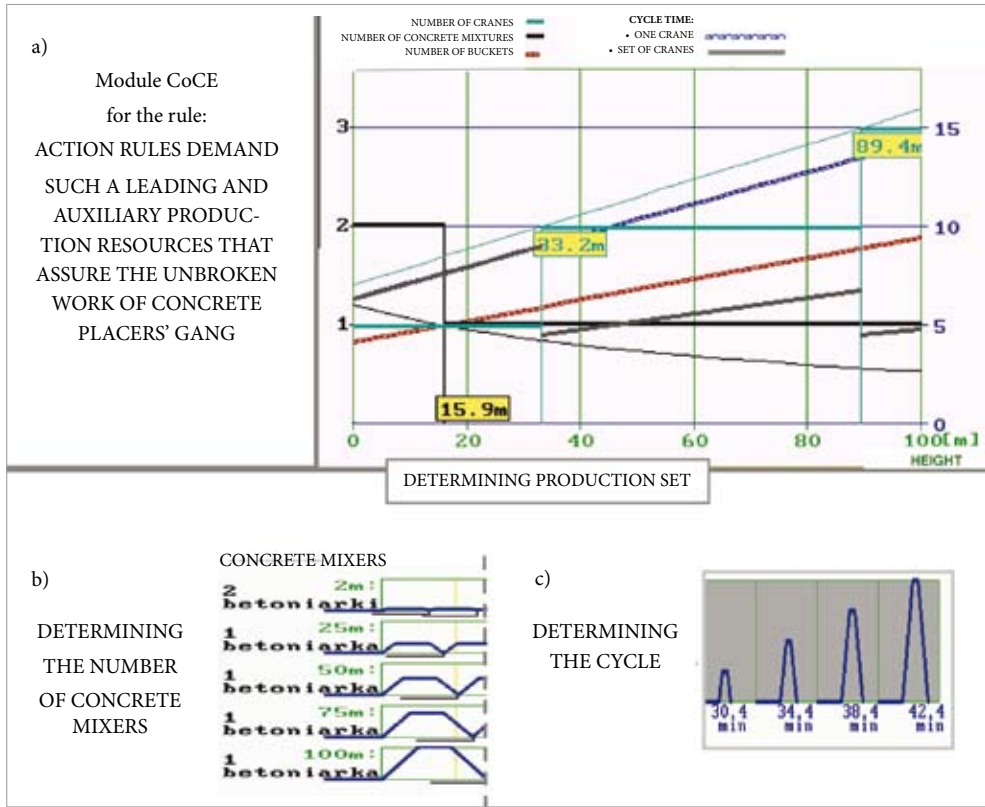
Fig. 7. An exemplary set of machines allowing for uninterrupted work of machines and groups of workers

CoCE module allows combining machines and groups of workers into production sets on the basis of decision-maker's preferences. As mentioned in the introduction, this issue is presented from the perspective of the overall operation of the expert system, but also it discusses the operation of individual modules. In the expert system rules which create the decision-maker's strategies have been specified. Although the example presented concerns silos building, rules formulated are of a universal character.

Using information saved in the system, the module generates production sets and simulates work of particular models. Fig. 7 presents a set combined on the basis of the following assumptions: work of leading and auxiliary production means and work groups, which must be uninterrupted. In order to meet the requirements, at a height of 33.2 m. to 89.4 m., a second crane had to be used. Above this height, 3 cranes had to be used (the number of concrete mixers has to be increased accordingly).

The program has generated solutions according to decision maker's preferences (see the rule in Fig. 7a) in order to keep the same level of efficiency during a whole realization. The rule was as following:

- If the harmonization of the elements is essential
- and the dynamic character of the process is taken into consideration
- and the number of the basic resources and auxiliary production materials is variable
- then determine the production set to realize the projected construction.

While considering the operation of an individual model, the problem concerns the manipulation of parameters used for ensuring a constant efficiency level of the system.

Diagrams at the bottom of the screen (Figure 7b) display a visualisation of the harmonic cooperation of the elements involved (cranes and concrete mixers). Part of the Fig. 7c shows changes of the length of the cycle of crane's work in minutes, when the height of the silo grows. The issues discussed are of theoretical character only; however, they illustrate explicitly a tendency of a phenomenon and work of inference mechanisms.

6. Conclusions

1. The submodel of a complex process has been designed in a way revealing selected features subject to the analysis. The research explores how changes that occur during the realization process (in this case changing the object height) affect the efficiency of the production sets involved. It has been demonstrated how the use of tools proposed can effectively eliminate difficulties encountered.

2. Modules presented as a part of the expert system illustrate that this is a modern device used for technology designing and work organisation. The two modules have revealed the nature of the modelled process. The results concerning the work of both modules show that a primary goal of this research has been achieved.

3. The system developed designs monolithic constructions in many aspects such as: selecting sets of machines, detailed analysis of work carried out by work groups, making schedules, and multi-criterion analysis. The system is still under development.

4. This article presented only some capabilities of the expert system. A capability of carrying out work simulations, designed in accordance with particular criteria reveals indiscernible in practice correlation between all elements.

5. Visualisation of simulation results makes it easier to comprehend a problem, facilitates communication between all participants of an undertaking and provides an in-depth insight into a complex investment construction process.

7. Acknowledgments

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MONOLITINĖS STATYBOS PROCESŲ MODELIAVIMAS

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Santrauka

Šiame moksliniame tyrime modeliuojami statybos procesai. Straipsnyje parodomas sukurtos ekspertinės sistemos funkcionavimas ir pristatomos analitinės pasirinktų modulių savybės. Pagrindinė modulių užduotis – pasiūlyti tinkamą gamybos sistemą, sudarytą iš tam tikro skaičiaus mechanizmų ir darbininkų. Kai kurie moduliai gali būti panaudoti tik tada, kai reikia atlikti gautų rezultatų modeliavimą ir vizualizaciją. Minėti moduliai yra ekspertinės sistemos, kontroliuojamos vartotojo, dalis. Įvertinant specifines duomenų savybes gali būti taikomos dvi modeliavimo taisyklių rūšys – mikro- ir makro-lygmens. Moduliai SiCE ir CoCE iliustruoja mikrolygmens taisyklių, apibūdinančių technologinius ir organizacinius procesus, veikimą.

Reikšminiai žodžiai: statybos operacijos, monolitinės statybos procesai, ekspertinės sistemos, modeliavimas, vizualizacija.

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