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FLOW-SHOP SCHEDULES IN CONSTRUCTION

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Abstract

It is a rare situation when Construction Managers have free hand to establish the optimal sequence of jobs (civil engineering objects, buildings, etc.) to be erected for to achieve say the shortest overall execution time. The order of jobs are typically determined by individual contracts (by clients) or by some practical considerations (accesses, logistics, technological relations, functions, etc.). It is less commonly known that with no other factors changed the sequence of jobs ab ovo define minimum overall execution time achievable. Within special conditions the sequence of jobs may have significant effect on minimum overall execution time, even more, this effect theoretically can be non-limited (!). The phenomenon is known and studied deeply in Operations Research (Management Science) for Manufacturing Industry (Production Management) and is referred as Flow-Shop Scheduling Problem. The paper is addressed to some managerial aspects of Flow-Shop Schedules – in fields of Construction.

Key words: construction management, scheduling, flow-shop

INTRODUCTION

Utmost effective arrangement of production elements in manufacturing industry is imaged by assembly-lines most famous early representative of which is Chicago butchers' disassembly line inspired production line fully introduced at Ford Motor Company in 1910 producing ten thousand cars a day in years of its maturity. This kind of arrangement of production processes not only provides the highest productivity at lowest unit cost in case of mass production, but also promotes mechanization integrating machine series in production procedures right to man-less totally automated manufacturing plants. This later sentence contains three key terms: highest productivity, lowest unit cost, mass production.

These key terms – better said pre-conditions or expectations – are not too easy to implement in Construction Industry. On-site production is highly exposed to disturbing effects and to changing conditions; pursuing lowest unit cost may lead to more and more incorrect and/or unsustainable market competition; and needs for mass construction is typical rather in post-disaster periods when fast and massive reconstruction/redevelopment is a key consideration.

This later was the case – for example – after World War II in Europe (especially in Middle and in Eastern Europe), and is the actuality in some disaster-stricken developing countries of our days too. Introducing and favouring so called "Industrialized Construction" resulted in frequently criticized districts (housing plants) of soulless uniform block houses and spiritless uniform public buildings still characterizing landscapes of bigger cities in countries of Eastern Europe. That was the era of Belt-System Construction, when troops of "workers' armies" had built thousands of houses of the same structure, when progression lines of succeeding jobs on linear schedules hastened to shape perfection – the ultimate parallels (See Fig. 1).

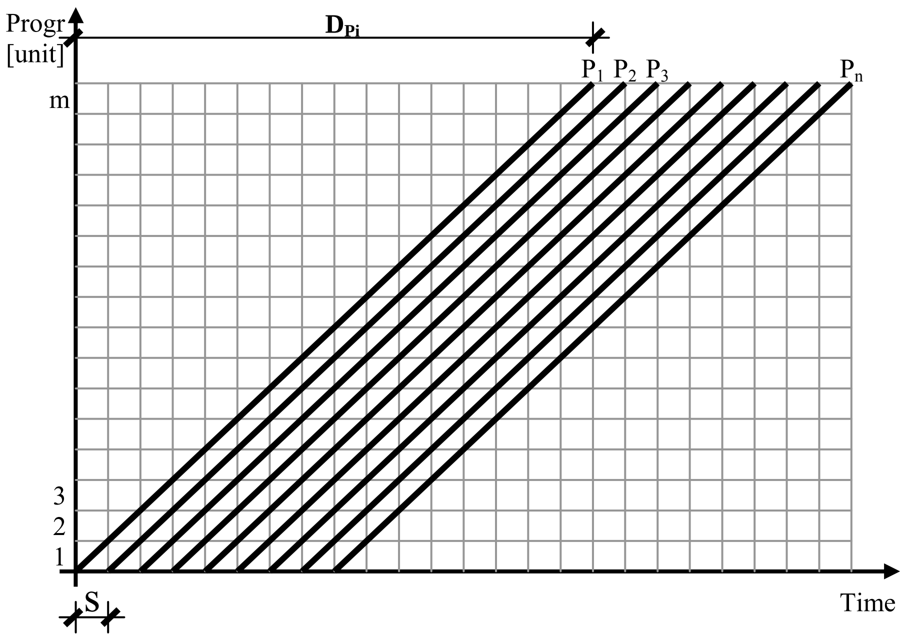

Fig. 1) The ultimate parallels – the Synchronized Belt

1 FLOW-SHOP SCHEDULES

Mass production – by its nature – can satisfy needs in quantity in a relatively short period, but due to changing expectations and needs for variety manufacturers soon faced the challenge of uneven production times (per unit) on units of machine series and confronting preferences of consumers (“clients”) and of manufacturers (“contractors” – in Construction Industry).

Though thinking it over in short it can be seen clearly it is less widely known that sequence of products (buildings) to be processed – when having the same machines (resources) assigned to all products (buildings) – may have significant effect on production (construction) time of individual products (buildings) and on overall production (construction) time of all.

Figure 2. demonstrates time effect of sequence of buildings (‘A’ and ‘B’) to be erected by the same two subcontractors (‘a’ and ‘b’). At top we see separate schedules with individual technological breaks (grey stripes indicating succession times between succeeding jobs) and combined ones below when all jobs are integrated in one common Master Schedule.

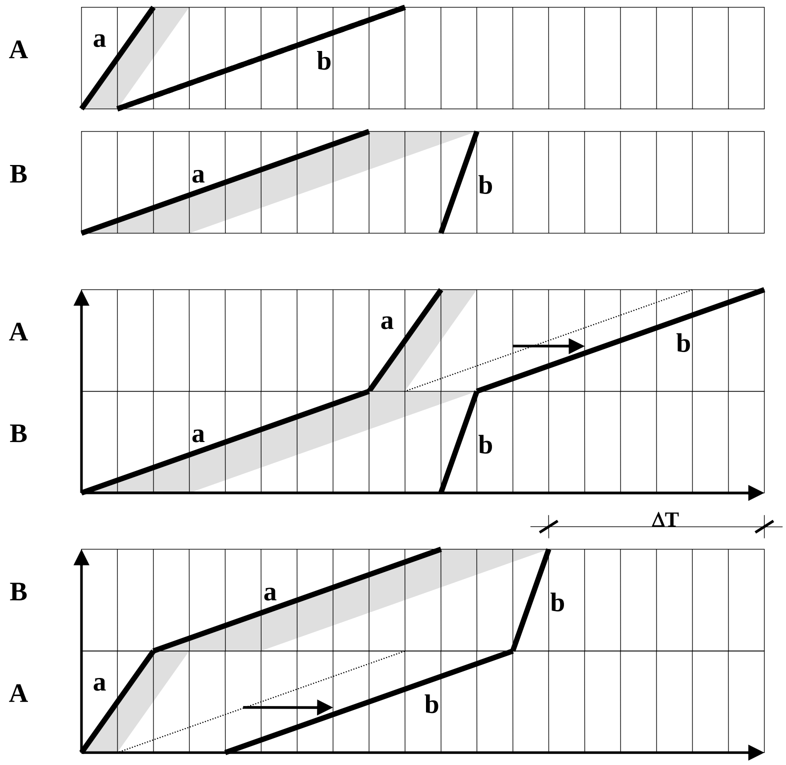

Fig. 2) In what a sequence?

Due to typically given (fix) technological order of processes (activities, jobs) on buildings of the same technology (first we build the foundation, after the wall, and after the roof, etc.) this effect may be multiplied – even more, theoretically can be unlimited (!).

Figure 3. demonstrates effect of sequence of series of two kinds of products (‘A’ and ‘B’) having different production times at succeeding machines. At product ‘A’ production time (D) on each second machine is significantly bigger than on the odd ones (which is nearly 0), while at product ‘B’ it is the opposite. Both product series consist of ‘m’ pieces of products (here m=3) and all of them are to be produced by the same ‘n’ pairs of machines (here n=3).

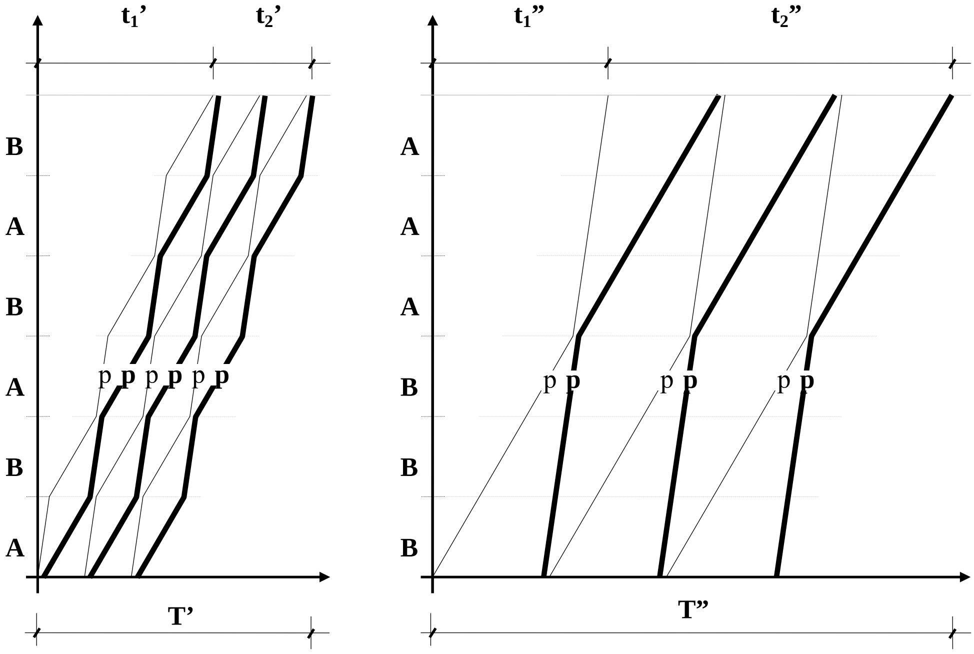

Fig. 3) Master Schedules having different sequences of the same products

When comparing overall execution time of the "best" sequence (T') and that of the "worst" (T'') increasing the number of units ('m') in the series and/or the number of pairs of machines ('n') we get the theoretical result "unlimited" (ratio of the two tends to be 0 – See Fig. 4).

$$\frac{T'}{T''} = \frac{t_1'+t_2'}{t_1''+t_2''} \approx \frac{m\cdot D_a + (n-1)\cdot D_a}{m\cdot D_a + m\cdot n\cdot D_a} = \frac{(m+n-1)\cdot D_a}{m\cdot(n+1)\cdot D_a} = \frac{m+n-1}{m\cdot(n+1)}$$

$$\lim_{m\to\infty}\frac{T'}{T''} \approx \lim_{m\to\infty}\frac{m+n-1}{m\cdot(n+1)} = \lim_{m\to\infty}\frac{m}{m\cdot(n+1)} + \lim_{m\to\infty}\frac{n}{m\cdot(n+1)} - \lim_{m\to\infty}\frac{1}{m\cdot(n+1)} = \frac{1}{n+1} + 0 - 0$$

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$$\lim_{\substack{m\to\infty\\ n\to\infty}}\frac{T'}{T''} \approx \lim_{\substack{m\to\infty\\ n\to\infty}}\frac{m+n-1}{m\cdot(n+1)} = \lim_{\substack{m\to\infty\\ n\to\infty}}\frac{m}{m\cdot(n+1)} + \lim_{\substack{m\to\infty\\ n\to\infty}}\frac{n}{m\cdot(n+1)} - \lim_{\substack{m\to\infty\\ n\to\infty}}\frac{1}{m\cdot(n+1)} = 0 + 0 - 0$$

Fig. 4) Theoretical effect of sequence on Total Execution Time

In a realistic case – of course – effect of sequence is not unlimited but can be so significant that restless endeavours are made in our days too to find optimal sequence of products in various production environments to achieve the best indices of various target functions.

In 1973 researchers had suggested a kind of reference system to identify scheduling problems by classification according to availability of machines and further restrictions completed by indication of actual target function [1]. Using this coding system our scheduling problem can be identified as F|overlap|C^{max} to be read as:

The job is Flow-Shop scheduling with no limit on number of machines (‘F’), where overlap in time is allowed at processing by succeeding machines (more machines can act on the same product in the same time) (‘overlap’) and the aim is to minimize the overall execution time identified by completion time of the last product (‘C^{max}’).

Flow-Shop as a basic class of scheduling problems embraces a set of conditions on production environment too:

- There are ‘m’ products to be scheduled on ‘n’ machines (each product must be processed by each machine);
- Order of machines at processing products is given and is the same for each product (technological order of machines is fixed and known);
- Order of products must be the same on each machines;
- Machines are performing their only job (special machines for each process);
- Processes are performed by single machines (one machine available for each job).

Substituting words of “product” and “machine” by “building” and “team” we can recognize preliminary conditions of establishing a belt-system construction [2].

To demonstrate variety of scheduling problems and their coding we may mention Job-Shop Scheduling (J), where technological orders of machines are given but may differ by products; P refers to situation when parallel machines are used and each machine can perform any job; ‘pre-emption’ indicates when processing of a product can be broken at machines; ‘idle’ refers to allowed workless periods of machines between succeeding products, while ‘no-wait’ warns us when it is unacceptable; ‘res1,res2’ identifies limited availability of resources; also target functions can be the minimum of sum of completion times (ΣC_i), minimum of sum of delays-, lateness- or tardiness (ΣD_i, ΣL_i, ΣT_i); and so on, to mention the most frequent ones only.

2 THE MATHEMATICAL CHALLENGE

One of the hardest challenges at scheduling Flow-Shop production is the so called “NP hard” or “non-polynomial” characteristic of the problem. Due to no existing polynomial algorithm (when number of needed steps of solution can be estimated as some polynomial function of size of set of products) exact solution can only be gained by some kind of enumeration and in extreme situations all possible sequences should be tested. To find the optimal sequence may need extremely long time [3].

To make it tangible: Assuming a super computer testing a million different sequences in a second it would take more than 77 thousand years to test all possible sequences of 20 products only ($20! = 2.43 \cdot 10^{18}$; $2.43 \cdot 10^{12}$ sec > 77000 years).

$F2||C^{max}$ (Scheduling m products on 2 machines) is one of a few delighting problems for which there exists a polynomial solution – first published by S. M. Johnson in 1954 [4]. Having more than two machines the problem seems to be stubbornly NP hard.

Integrating special needs and more realistic conditions of Construction Management typically implies extension of the original problem even more deepening difficulties of finding optimal solutions and of proving their optimality.

For example:

Restriction of "uniform order of machines on products" ("uniform technology") would be hurt (should be released) at situations when not all machines (all jobs) are needed to produce each products ("missing jobs allowed") – though relative order of machines remain the same. (See Fig. 5)

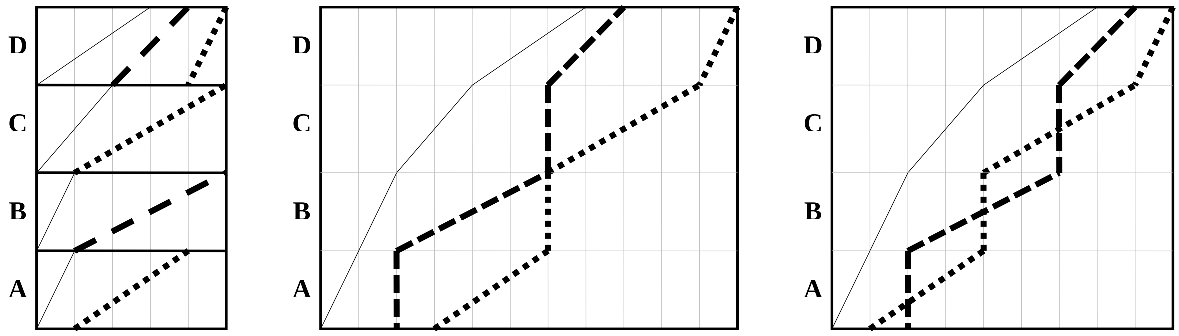

Fig. 5) "No missing jobs" and "Missing jobs allowed"

Setting restraint of "no idle times" would eliminate possibility of resolving paradox situations when – proportionally or virtually – increasing duration of an activity results in decreasing overall execution time. (The phenomenon is know as "Duration Paradox") (See Fig. 6)

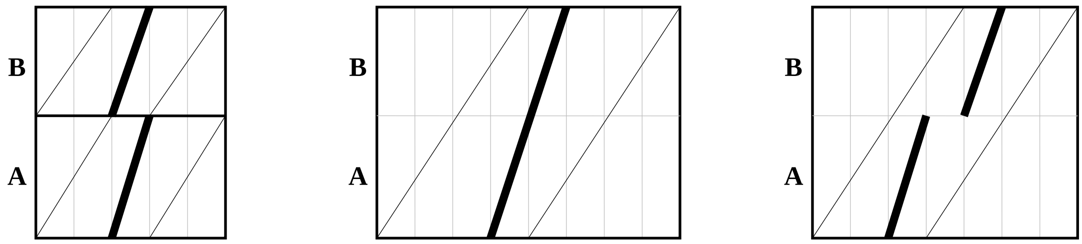

Fig. 6) "No idle times" and "Idle times allowed"

Special needs (e.g. technological breaks, manipulation areas) of construction – especially at performing finishing jobs or installing building mechanics – can generate situations when releasing restraint of "order of products on machines should be the same" (and "passing" gets be "allowed") can result in time savings too. (See Fig. 7)

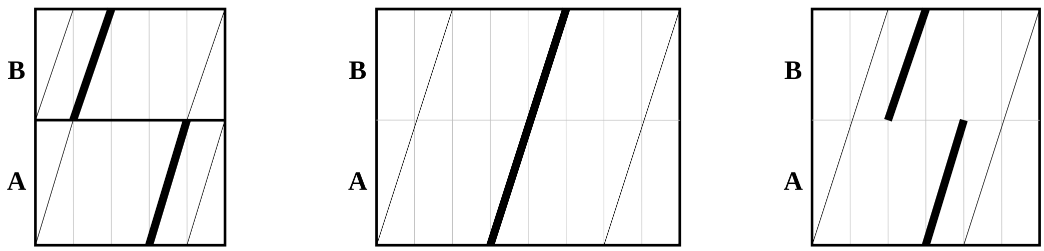

Fig. 7) "No passing" and "Passing allowed"

Most characteristic difference between Manufacturing and Construction management is that at manufacturing the product is moving from machine to machine, while at Construction machines (teams) are moving from product to product (from building to building). Typical size of a construction product (building) enables more machines (teams) working on it ("overlapping" – machines in time when processing the same product is – "allowed"). These differences vanish when considering manufacturing sequences of whole product series or when “building” large products (ships, aircrafts, etc.) and also when constructing structures (buildings) of strictly limited accesses. (See Fig. 8)

On Figure 8. P_i denotes Process *i*, D_i represents duration of process *i*, F_i is for succession time after Finishing process *i* and S_i is for that after Starting process *i*, while CR_i stands for a technological break after process *i* – in general.

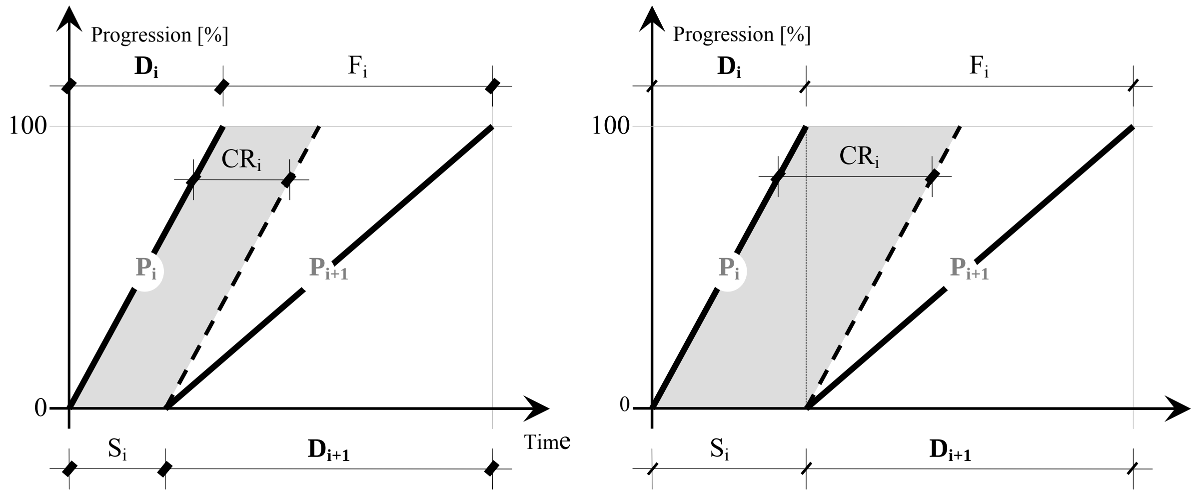

Fig. 8) “Overlapping allowed” and “No overlapping allowed”

… And optimal solution of a variant (of Flow-Shop Problem) – against all expectations – can not be derived from optimal solution of an other variant (of it)!

Flow-Shop problem seemingly provides everlasting wide fields for researchers to develop newer and newer principles and algorithms for to turn the unbeatable to a practically useful tool (e.g. [5]). Special Issues of Scientific Periodicals are regularly publishing summaries or comparisons of new achievements (e.g. [6]). The latest branches of researches are testing combinations of (heuristic) algorithms and/or intelligent search engines (memetic algorithms) while finding a relatively good solution for practical use tends to be preferred rather than achieving a theoretically optimal one (e.g. [7]). At Department of Construction Technology and Management of Budapest University of Technology and Economics also tough efforts have been made to bring theoretical ways of finding optimal schedules closer to daily practice. As part of research a special software have been developed to provide exact solution for variants of scheduling problems having been also equipped with facilities to test theorems and ideas of various other approaches too.

After modelling and testing potential effects of sequences on total execution time of a master schedule we tested five principal ways of developing optimal schedules:

- For to gain certain optimum and to check any other trials enumerative algorithms had been developed, later improved and accelerated by some methods of filtering (Total-, Partial- and Implicit Enumeration);
- Building sequence as a kind of series of optimal matches with the hope of deriving the problem back to a kind of Assignment Problem so it could be solved by Linear Programming (Arranged Branch & Bound);

- Finding partially optimal solutions for simpler cases and combining them for more complex situations. Adapting some fast and proved algorithms to our purposes (Johnson's Algorithm);
- Producing an initial sequence and improving it gradually via series of consecutive modifications (Pair-wise Exchanges);
- For to test/measure return on all our efforts, a pure and primitive way of finding optimal sequence – by chance (Random Sampling).

After long time of examinations, after numerous trials and hypotheses falling apart as leaves from trees none of the principal ways above proved to be either the only or the best way of constructing/finding optimal sequence. None of the "advanced" techniques and/or approaches proved to be either unquestionably or more outstandingly better or effective for our purposes than the most primitive way of Random Trials. But the same time we found that elaborating a proper estimate on likely optimum is more promising a challenge. Having it, we could judge optimality of any sequence found or produced, and we could judge likely return on our efforts to find an even better solution if the one present would not serve our satisfaction [8].

3 THE MANAGERIAL CHALLENGE

Our original intention was to resolve conflicts of preferences of individual clients and those of contractors contributing in construction projects. A synchronized belt would represent not only highest efficiency at utilizing available resources, but could provide shortest overall execution time of all- and shortest completion time of each individual products/buildings too.

Understanding and accepting a proper sequence of buildings by both parties (clients and contractors) could also promote conflict management and achieving project goals too [9].

When thinking of Belt-System Construction (Flow-Shop Schedule) we typically assume a large common resource pool (assembly-line) being set for to build (produce) mass amount of buildings (products). There are two problems with that statement in our days: 1.) No common resource pool (such as ones possessed by typical state owned construction companies in East European countries some decades ago) exists; 2.) No mass need (for new-built uniform/typed houses) exists.

Huge state-owned construction companies falling apart large number of small independent specialized companies appeared on construction market. No central (state-owned) investment ("National Development") Departments (even no dedicated-, or powerless government of it), but huge bulk of individual development "projects" having their own individual preferences. Project Management rules over Construction Management – destructive effect of which can be traced throughout the World, even in developed countries too.

Mathematics behind is less problematic! We can find optimal solution for sequencing our jobs – of course, not as solving a pure Flow-Shop Problem. The bigger conflict emerged – from managerial aspects – is that Schedules of this kind (Belt-System Construction) and especially optimality of it is extremely sensitive to any changes in conditions or in data considered. A slight change in a duration and optimality of the sequence developed turns to be questionable. With the new modified set of data or amongst the new conditions there might be another sequence proving to be optimal – and the new optimal sequence hardly can be derived from the original one. And – due to the relatively long completion periods – construction is highly exposed to changes of any kind (plans, expectations, regulations, environment, etc.).

Also, in era when Belt-System Construction (or “Industrialized Construction”) was favoured and promoted not only mass needs for new-built homes and infrastructure characterized economies of “still developing” countries, but lack of available resources too. In developed economies there are “abundant” promptly available or soon accessible resources. In our days – due to economic crisis – conflicts are spiring at over-capacities, resulting in unsustainable market competitions and/or in intensive migration of working power, even more, in masses of skilled work forces discarding their original professions …

Economic environment seemingly does not promote application of Flow-Shop Schedules in Construction in our days. But before some starts to bury potentials in Flow-Shop Schedules we should turn our attention to smaller scales and partial jobs of Construction. We may think of not only whole complex buildings but performance of some dominant resources (machines, craftsmen, material), some key technological processes, or – interchanging the two axes of a linear schedule – the technological order itself of some (likely “finishing”) processes too.

Seeing endeavours to decrease weather- and labour-exposed characteristic of construction Flow-Shop Scheduling may play its role at prefabrication and/or in phase of product planning (of system elements of e.g. steel structures, formworks, building services, etc. to be installed).

Technology defines appropriate order of processes generally. But at some large-scale regional developments where fleets of heavy machinery are to be applied expectation of most effective operation of expensive machinery may force rethinking feasible technological orders and/or sequences of sub-tasks to be performed.

We also have to keep in mind that if something was constructed, it must be maintained, repaired, reconstructed or demolished too. Panel houses of past decades having built in large amount now are in state of necessary renewal – generating massive need for reconstruction.

Finally: Till now we had focused our attention on mass production, on massive needs, and had forgotten the other side, the case of strictly limited access of resources. As a paradox of developed economies – due to economic crisis generated migration and discarding mentioned above – when demands tend to emerge we may get in situation where lack of skilled workers and insufficient experiences grow to a leading problem – as it can already be detected at some traditional professions (e.g. masons, carpenters, tinsmiths) and at some investments of high priorities.

Flow-Shop Scheduling is an interesting and ever-challenging mathematical problem. Though it is relatively rare a situation in Construction when we are free to determine the order of jobs to be performed, we have to keep in mind that establishing a proper sequence may inhere potentials of improvement, and we must not forget contrary effects of forgetting about it. As university teachers at BUTE DCT&M, intending to widen complex view of our students by curricula we lay special emphasis on calling their attention to possibilities and consequences of merely choosing the proper (say: “optimal”) sequence for performance.

4 CONCLUSION

Flow-Shop Scheduling is a famous ‘NP hard’ problem in fields of applied mathematics. Being developed for to model manufacturing mass amount of technologically similar products on assembly-lines it can be considered as an ancestor of belt-system construction of past decades in Eastern Europe when industrialized methods had been adapted in construction to satisfy mass construction needs in a relatively short time in a scarce economic environment.

Studying possibilities of applying Flow-Shop Scheduling techniques for to develop optimal schedules of mass construction we find that contemporary economic environment does not support it. No mass need, no lack of technical resources and no common resource pools. Own preferences of individual projects are also not promoting sequential development strategies.

In a changed economic environment expectations against sequencing should be re-judged. It may help achieving common project goals. It may help increasing efficiency of utilization of resources at prefabrication and it can guide us when designing large regional infrastructural projects too. But most of all: it can play essential role in bringing attention of philosophers and practitioners of construction management that changing age-old traditions (e.g. when scheduling onsite jobs) or developing a proper sequence of objectives (tasks, buildings) may result in significant savings in time-spans – and in all other efforts.

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