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# AGILE/FLEXIBLE AND LEAN MANAGEMENT IN READY-MIX CONCRETE DELIVERY

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The aim of the article is indicating the advantages of utilizing the synergy obtained by introducing two management methods: Lean Construction and Agile Management using the example of the process of deliveries of concrete mix in road construction. Despite the seemingly contradictory assumptions (Lean Management aims at limiting wastefulness and maximizing the value for the customer and agile management serves for creating the possibility for fast, effective response to non-expected changes thanks to the adopted strategy of flexibility, which usually requires engaging additional resources), both management methods deliver the effect of increasing the effectiveness of the machine laying the pavement. Using a "spaghetti diagram" (one of the tools of Lean Management) led to limiting the time losses during loading and unloading the concrete mix destined for constructing highway pavement. On the other hand, the tactic of technological flexibility in the form of a modification of the concrete mix allowed for broadening the time frame for the delivery of concrete to the construction site to as much as two hours. Moreover, applying the real time delivery management system (in accordance with the assumptions of Construction 4.0) created the possibilities for ensuring quick reacting to the changing conditions of delivery and laying the concrete mix in the pavement and ensuring the appropriate functioning of the machine laying the pavement. The presented examples indicated the advantages of the suggested concept in reference to the traditional solution.

*Keywords***:** Agile/Flexible, Lean, highway construction, simulation. RMC delivery, real time management

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# 1. INTRODUCTION

While analysing the implementation of construction contracts, it is necessary to draw attention to the increasing problems which are demonstrated, above all, in exceeding the budget, delays in the implementation of particular phases, quality reservations and the loss of financial liquidity. This causes numerous misunderstandings and disputes, which frequently lead to long-lasting lawsuits and, in consequence, to the bankruptcy of companies etc.

On the basis of the experience of the authors and the available literature, the factors favouring the mentioned problems include:

- the systematically growing scale of construction undertakings [1],
- changes in the project (also in progress of the implementation, e.g. a change of the assortment, of the amount and time of delivery of ready-mix concrete on the day of the planned delivery),
- low intensity of work in the initial implementation phase of the investment (this refers to the period of the first 3-6 months from signing the contract or from obtaining the permit for the implementation of an assignment),
- problems with the coordination between various industries participating in the undertaking (high degree of complexity of undertakings),
- long quality chains (difficulties with quality management resulting from the co-responsibility of various participants of the construction processes - with frequently conflicting interests)
- the impact of the changing surroundings (the implementation of processes usually in an open area), which demonstrate strong changeability, high uncertainty and significant complexity
- the production is usually of a prototype nature - even in case of a typical project, the differences will result from local geotechnical conditions, the specific local composition of the participants of the undertaking etc.

It seems that an element which may contribute to resolving these complicated problems is improving the methods of managing processes, undertakings and organizations, that are engaged in the process of implementation of these undertakings. While observing the systematic progress in the field of production management, one can notice opportunities based on the implementation of methods successfully applied in other fields of economic activity (Six Sigma [34], Flexible Management Systems, Agile Management, Lean Management, digital technology [35], Industry 4.0 [36] etc.). At the same time, it is necessary to pay attention to the fact that the introduction of methods of this kind in the field of the construction industry is possible on the condition of taking the specificity of the construction industry into account. An element which is of significant importance is the delay in the implementation of innovative solutions in the construction industry - also in the area of management, an example of which may be the application of ICT in the construction industry - the construction industry ranks 20th among 21 sectors of economy (worse achievements in this field are only demonstrated by agriculture) [42].

The aim of the article is demonstrating the beneficial effect of the synergy between Lean Construction and Agile/Flexible Management and of simultaneously applying real time management compliant with the Construction 4.0 idea during the implementation of the production process, the transport and paving the concrete mix into the road pavement. The achieved synergy allows for limiting the influence of disruptions on the process efficiency (ensuring the continuity of operation of the machine laying the concrete mix with the assumed efficiency).

After presenting the motivation for the implementation of the proposed RMCD4.0 (Ready-Mix Concrete Delivery 4.0) method, the aim and the content of the article in point 1, point 2 presents the state of knowledge referring to both, the general development of management methods, as well as the state of knowledge in the scope of managing deliveries of ready-mix concrete. Point 3 presents the proposed method, tentatively called RMCD4.0 in order to underline the decisive role of the Industry/Construction 4.0 industrial revolution. Point 4 describes the construction of road pavement from cement concrete with taking into consideration both, the traditional approach in the management of the deliveries of ready-mix concrete, as well as taking into account the assumptions of the RMCD4.0 method. Point 5 presents the results for both cases presented earlier and point 6 demonstrates the conclusions and the perspectives for further research.

The original contribution of the authors is based on the combination of two methods associated with the idea of improving the flow: Lean and Agile Management as well as management on the basis of a simulation model in real time basing on the quasi-deterministic approach (compliant with the Construction 4.0 idea).

## 2. THEORETICAL BACKGROUND

### 2.1. Development of management methods

The basic problem in the management of construction processes is the difficulty with achieving compliance between the plan and the implementation. As was rightly pointed out by Drucker, in the practice of management the element which plays the key role is information and the possibility to manage it [2]. The dissemination of mobile devices and of wireless monitoring systems with the option of localization is the condition of the functioning of the proposed system. On the other hand, a significant element is the preparation to changes instead of the "optimization" of costs through the maximization of profit based on stiff procedures [3]. It is necessary to remember that organizations are socio-technical systems composed of technical subsystems (structures and technology) and social subsystems (goals and culture). According to Emery and Trist [4] technical subsystems are defined in a deterministic way (their behaviour is fully predictable) and social subsystems are probabilistic. Kostera [5] polemizes with that view, indicating, that all the subsystems of an organization are probabilistic in nature, although it is possible to indicate aspects of a deterministic or quasi-deterministic nature. This article has been based on these assumptions - the aim of the management of a system of deliveries of ready-mix concrete is the pursuit to build a model of a quasi-deterministic nature. Thanks to the possibility to collect information, process it and make decisions in real time, we are able to act towards a quasi-deterministic system which ensures rhythmical deliveries of concrete mix, despite the occurring disruptions. An element which cannot be overestimated is also access to prognostic information (referring to e.g. the transport time with taking into consideration the alternative routes) - near real time management.

An element which is also important is resigning from wreckage economics [6]. The point is not to squeeze the maximum out of everything, but to try to maintain continuity of operation - that requires agility/flexibility.

It has to be underlined that the construction of a strictly deterministic model in reference to construction processes seems particularly difficult due to numerous problems resulting, above all, from work in a dynamically variable environment. Thomas and Ellis [7] indicate many potential reasons for problems in the planning and implementation of construction processes:

- planning (problems in applying such traditional methods as schedules or network models in the conditions of risk and uncertainty)
- the development of the construction site - the complexity of planning in this scope has to be underlined - the progress of the works forces changes in this scope, however, the non-compliance between the implementation of the plan and reality may generate disruptions (e.g. the necessity for demolition and for performing the construction anew from prefabricated elements of an appropriate quality)

- the weather conditions - it is possible to indicate three basic situations: (1) the works at the construction site are interrupted with the assumption of applying hourly remuneration rates, (2) the works are continued but with reduced efficiency due to unfavourable weather conditions and (3) demolition and constructing a new is necessary as a result of continuing the works in unfavourable weather conditions; it also has to be underlined that some atmospheric phenomena force a longer interruption in the course of the planned construction works than the duration of the disrupting phenomenon (e.g. heavy rain not only requires the interruption of variable works during the fall but also after it stops)
- managing deliveries, storing and the transport of materials at the construction site - especially in case of ready-mix concrete this is of significant importance - attention has to be paid to the limited possibilities of using the nominal capacity of concrete mixer trucks due to the carrying capacity of the access roads, the influence of the changing weather conditions on the conditions of maturing and laying of the concrete mix (especially the temperature or precipitation)
- managing employees is a problem which is especially important - unfortunately, the construction industry demonstrates an exceptionally high share of non-value added time in comparison to typical factory production [6, 7]
- the planning and the coordination of the implementation of processes/operations is of high importance due to the necessity for collaboration and the mutual dependence between processes - for example, the frequent awaiting of the concrete mixer truck for unloading at the construction site may result from the lack of the preparation of the boarding or from the reservations of the supervision or/and the engagement of the crane lift in many processes at the same time - naturally, the reason for the delay may also be withholding the works due to the mentioned difficulties resulting from unfavourable weather conditions
- the collaboration with subcontractors is an increasingly serious problem due to the fact that many general contractors eliminated their operational employees who used to perform particular processes at the construction site and are operating basing on their own staff managing subcontractors - this is frequently associated with the risk of congestion, i.e. a too high number of employees/equipment on a given work plot, which usually results in reduced efficiency (according to Thomas and Ellis, in order to ensure the due efficiency, the area per one employee must be equal from 23 to 28 $m^2$/person [7]).

By analysing the above mentioned problems, it is possible to indicate several directions for improving the management of construction processes [8, 9, 10, 11]:

- basing more on a win – win strategy - partnership (long-term collaboration) [12,13]
- elimination of errors/higher quality of design works – basing on BIM and VR [9,14]
- improvement of logistics and of the management of supply chains, circular economy [15, 16]
- execution at the construction site (on-site) based on management compliant with lean and agile/flexible management [11,19]
- innovative technologies (innovations: material/process innovations, digital and wireless technologies, simulation technologies and CPS) [17, 18, 20].

For three of the above mentioned directions of improvement considered in the discussed concept of the RMCD4.0 method (partnership, execution at the construction site based on Lean and Agile/Flexible Management and innovative technologies) – the potential of benefits ranges from 28% to 34% when total efficiency is compared [8]. Two of them (Lean and Agile/Flexible Management) have been more closely discussed below.

**Brief history of Lean, Agile/Flexible Management**

Without going into detail into the history of quality management, it is worth to mention that the current methods in this field may be classified [21] as located in the area directed towards flexibility and openness, while Scientific Management (1900-1930) may be classified in the quarter dedicated to organization and stiffness and Human Relations (1925-1970) - in the quarter associated with unit stiffness (closure). Currently, the preferred methods are based on integrated management which, benefiting from the current achievements (the neo-classical and the neo-behavioural school), take into consideration a system view and a situational view. Moving to the topic presented in this article, a short history of Lean and Agile/Flexible Management has been demonstrated in table 1. Lean Construction may be most briefly defined as a way of designing production systems with the assumption of waste minimization (materials, time, labour) in order to generate maximum value [31]. Agile Construction, in turn, may be defined as a management method which allows for fast adaptation to changes (e.g. at the construction site), usually basing on flexibility; this ensures achieving greater effectiveness of operation [33].

Table 1. Brief history of Lean and Agile/Flexible Management

| Time period | Lean | Agile/Flexible | Remarks |
|---|---|---|---|
| **1931-1950** | First application Toyoda idea jidoka - not car production – 1930s | Flexibility in the economic development – Schumpeter 1934 | |
| **1951 – 1970** | Just in Time implementation in Toyota Factories (1950s-1962) | First application of flexible design [1960s Ponte 25 de Abril - Lisabonne] | |
| **1971 – 1990** | Toyota Production System (Ohno 1988) ] | First work in flexible design for infrastructure [R. de Neufville 1972]] | |
| **1991-2010** | First Lean Construction [Koskela 1992] International Group of Lean Construction 1st Conference -1993 Last Planner System published [Ballard 2000] TFV approach [Koskela 2000] Integrated/Lean Project Delivery [Matthews and Howell 2005] | Flexible strategies [Evans 1991] Agile Manifesto [2001] Agile Teams (Kent Beck 2004) Is Agile Project Management applicable to construction? [Owen et al. 2006] Agile Construction for the electrical contractor [Daneshgari 2010] | |
| **2011-2020** | 1st Workshop When Social science meets Lean and BIM – 2013 Lean Construction/IoT [Dave et al.] 8th Workshop – 2020 postponed to Apr 2021 28thConf. of IGLC- 2020 | Flexibility in Engineering Design [de Neufville&Scholtes 2011] Project Management 2.0 [Leavitt 2011] Agile Project Management for other industry [Conforto et al. 2014] 1st International Workshop Flexibility (2015) Agile in PMBoK 6ed. [2017 PMI] Prince 2 with Agile [2015] | Industry 4.0 – 2011 |

As may be concluded from Table 1, both of the discussed approaches originated in the 1930s, at least 90 years ago. In case of Lean, it was the application of a system of automatic turning-off of a device (a loom) in case of a break-down (a broken thread), and in case of flexibility the aim was applying flexibility in the financial field. It seems that the element connecting both approaches is Integrated/Lean Project Delivery [22] and Agile Teams [10]. In both cases the aim is the collaboration of the team managing the undertaking (with taking into consideration the everyday contact between the customer and the team at the construction site). This, assumedly, small team is able to, on a current basis, solve the problems which appear every day (the assumption is that they will keep appearing and the plan will undergo gradual changes). An element which may be considered a significant difference is the fact of multi-annual tradition of conferences and workshops in the area of Lean Construction – in 2020 the 28th IGLC Conference and the 8th Workshop were organized, while in the same year only the 5th International Workshop - Flexibility in Sustainable Construction was held. A significant matter is taking the Agile/flexible approach into consideration in standards for managing construction projects in the USA (PMBoK 6th edition [23]), as well as in the UK (PRINCE2 Agile [24]).

### 2.2. Management of ready-mix concrete delivery

Disruptions of the production processes, of deliveries and of paving the concrete mix result from many factors, however the one which seems to be of key importance is the very frequently applied division of the traditional production process, of the transport and of paving the concrete mix at the construction site, which was originally performed within one organization, between three independent entities: the manufacturer of the concrete mix, the carrier specialized in the deliveries of ready-mixed concrete (who usually possesses concrete mixer trucks, tipper trucks and concrete pumps which are only applied for this) and the team performing the preparation and the paving as well as the curing of the concrete mix until the required parameters in the pavement are achieved. A significant element of the functioning of the concrete batching plant are constant changes of deadlines and of the amount of the ordered concrete mix which frequently take place in the last moment and refer to the vast majority of orders (75-95% of orders according to Durbin and Hoffman [25]). An additional complication is the random nature of processes which - naturally - one can try to control (models based on normal distribution seem to be not always suitable for the simulation), however, an element which is always significant is the question about the current course of a given process (e.g. deliveries of concrete from the manufacturing plant to the construction site) in a given moment of reality (the moment from $t_{k-1}$ to $t_k$) in accordance with the elaborated model which is verified with more or less compliance. Naturally, a big facilitation is the fact that the localization of the devices transporting the mix may be performed with sufficient accuracy with the use of commonly applied equipment (wireless devices with the localization option).

From the point of view of managing deliveries of ready-mix concrete, 4 stages of development may be differentiated based on the new idea which opened further, new possibilities for improvement:

1. Applying operational studies
2. Introducing simulation as a tool for process management
3. Using management systems based on the localization of concrete mixer trucks
4. Using the possibility of real time management - based on industry 4.0

In the first period, two significant works have to be noted:

- The description of the transport problem (TP) created by Hitchcock in the year 1941 [26].
- The description of the Vehicle Routing Problem (VRP) proposed by Danzig and Ramser in the year 1959 [27].

The first one refers to planning deliveries of goods from many dispatch points to many reception points with optimization due to the minimization of costs, whereas we assume balancing the product from the point of view of the production volume and the order volume. It is obvious that it is difficult to ensure such balance in a real model of deliveries of ready-mix concrete. Moreover, it requires meeting additional conditions due to the necessity to ensure the continuity of paving concrete and the variability of the characteristics of the concrete mix over time. Further works referred to subsequent versions, e.g. the Chinese Postmen Problem – CPP – a combination of the VRP and Arc Routing Problem – ARP [37] or the Rural Postman Problem [38]. Generally, these solutions will lead to indicating to which reception points a product is supposed to be sent from a given dispatch point.

In 1973 Halpin elaborated the CYCLONE software for simulating cyclical construction processes; the software was based on the Monte Carlo [28] method. Naturally, these methods were developing over these almost 50 years. An example is the STROBOSCOPE and the EZStrobe software developed by Martinez [30]. An achievement in comparison to the previous solution is the possibility to capture the collaboration between systems, e.g. the deliveries of concrete with the use of a concrete mixer truck and a working team paving the concrete mix at the construction site. However, an element which always remains is the following significant matter: to what extent the analysed model refers to the delivery of X m3 to the Y construction site, which is supposed to be delivered at the hour Z of a given day.

The third developmental step in the field of managing the process of ready-mix concrete deliveries were systems based on applying the GPS and other systems allowing for the localization of concrete mixer trucks and tracking them almost in real time [29]. Of course, an element which still remained a problem were the changes taking place in actual systems, which referred to, above all, the cancellation or shifting of the delivery and the variable conditions of the transport (currently – Google Maps) and of the handling time at the construction site.

The Construction 4.0 idea (based on the Industry 4.0 idea announced as the 4th industrial revolution in 2011) which is currently being introduced provides the possibility to combine in one whole the planned solutions (based on the above mentioned methods) and the currently performed operational actions based on data obtained in real time and on updated forecasts. As a result, thanks to the synergy obtained for the CPS system (Cyber Physical System) constructed this way, we have the possibilities to ensure a stable rhythm of cyclic construction processes basing on the quasi-deterministic model. The dissemination of mobile devices allows not only for the current localization of concrete mixer trucks in real time, but also for planning further actions (e.g. the next rhythmical delivery without the necessity to create a queue of concrete mixer trucks in order to ensure the continuity of operation of the concrete paver.)

From the point of view of the new tendencies it is necessary to mention the pursuit to take into consideration not only the factors associated with the analysed construction process (quality, costs, efficiency), but also the factors associated with sustainable development [39]. To sum up, it is necessary to mention that the discussed methods of solutions for the problem of deliveries of ready-mix concrete do not exclude the better compliance of the model which is compliant with the transport algorithm or with the mass servicing model than with the simulation model [40, 41].

## 3. THE RMCD 4.0 METHOD

The basic problem in the management of the deliveries of ready-mix concrete is the non-compliance between the planned deliveries of concrete and their implementation. The proposed solution is based, above all, on the idea of combining two basic processes: planning and implementation in one coherent whole.

In respect of the complexity and the size of the problem to be solved, it is logical to divide it into three stages (fig. 1):

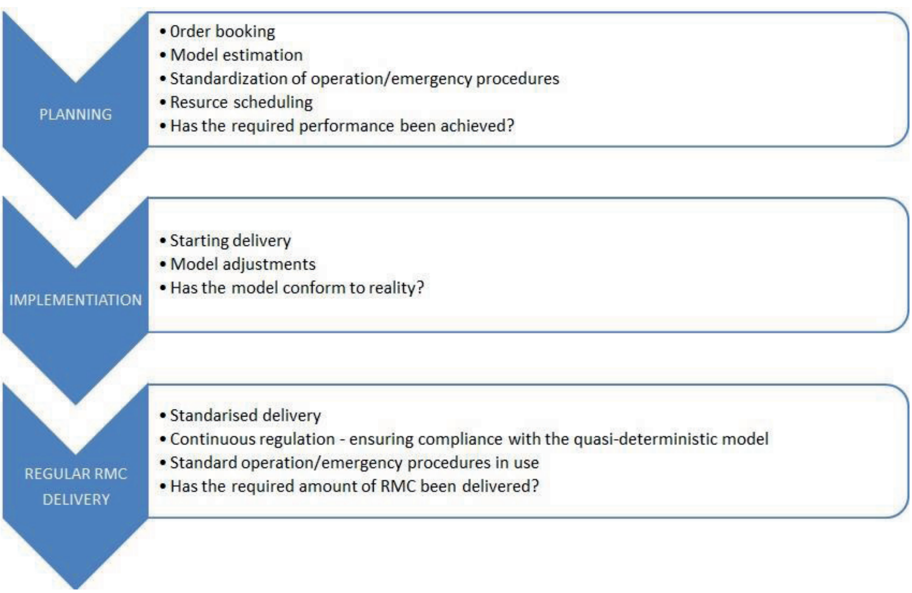


Fig. 1. The main stages of the RMCD4.0 method

**Planning** (planning orders, planning arrivals of concrete mixer trucks = the development of a simulation model) - the plan refers to the subsequent day

**Implementation** (introducing potential corrections) - it may refer to 1-2 h of observation of the system's functioning in real conditions

**Regular delivery of ready-mix concrete** (on the planned day) - current functioning of the control based on the simulation model and corrections in real time in order to achieve the planned results (the maximum efficiency of the concrete paver).

An element which deserves special attention here is the achievement which, thanks to the commonness of application of wireless devices equipped in localization systems, allows not only for tracking processes which are in progress, but also making decisions in the near future.

The theoretical bases of the adopted concept are based on the TFV theory created by Koskela 25 years ago [31]. It assumes managing construction processes from the point of view of three independent concepts:

- **Transformation** (classical approach: INPUT – PROCESS – OUTPUT)
- **Flow** (putting emphasis on ensuring flow without disruptions)
- **Value** (taking into consideration the processes which bring value for the customer – based on quality).

The basic elements of this concept were given in Table 2.

Table 2. The TFV concept of managing construction processes - based on [31]

| TFV element | Transformation | Flow | Value |
|---|---|---|---|
| **Concept** | Black box INPUT/OUTPUT | Flow stability | Value for the customer |
| **Main principle** | Getting production implemented efficiently and effectively | Waste elimination, reduce variability, increase flexibility | Ensure that all requirements get captured |
| **Based on** | Cost | Time /productivity | Quality |

As may be concluded from the above table, the FLOW approach is based on the simultaneous application of Lean Construction and flexibility (as the key element of Agile Management). In this perspective, the emphasis is on eliminating wastefulness, which leads to focusing on processes which deliver added value. However, in the construction industry, taking into consideration the typical problems associated with the disruptions of processes - it is necessary to also take into consideration the increase of flexibility which, from the Agile Management perspective, allows for fast adjustment to changes.

To sum up the presented concept from the point of view of theoretical bases, it is based on the following triad:

- Lean Construction – limiting losses/wastefulness,
- Agile Management (based on options, tactics and strategies of flexibility) for the purpose of fast and easy adjustment to changes
- Construction 4.0 – in order to enable communication in real time.

As a result, the analysed process of the production, of deliveries and of the paving of the concrete mix took into consideration the possibilities of introducing flexibility and lean construction in the following form:

- Ensuring stable time of loading the concrete mix (Lean Construction – the elimination of redundant activities in the form of e.g. preliminary loading of materials to the containers and shortening the time of collection of documents - the documents are delivered to the driver by the dispatcher),
- The scope of modification of ready-mix concrete - using lignosulfonate-based admixtures which improve the moistening of cement grains by make-up water. This results in the formation of a homogeneous cement paste which demonstrates low forces of internal friction, which ensures better workability of the concrete mix and stabilizes the properties of the concrete mix in time - in case of a significant technological risk of a too long delivery time,
- Ensuring a stable time of delivery (and return) thanks to monitoring alternative routes with the preference of the highest possible share of technical roads in the considered route and controlling the deliveries in a proactive way,
- Ensuring a stable unloading time - using the container of the concrete paver as a buffer container for the concrete mix (it allows for the further work of the concrete paver despite a lack of deliveries for about 0.5 h).
- Introducing rhythmical deliveries of both types of mix thanks to applying two types of trucks transporting the concrete mix (4-axis trucks for paving the upper layer of the pavement and 5-

axis trucks for paving the lower layer of the pavement) in an appropriate arrangement which ensures the synchronization of the machine set at the construction site.

The basic effect of the presented RMCD4.0 method is ensuring rhythmical deliveries of the concrete mix thanks to continuous monitoring of the processes in progress and of the surroundings. What is very important, the concrete mix had to maintain constant parameters of aeration and consistency due to the requirements of the specification and due to the applied slipform method.

## 4. CASE STUDY - AN EXAMPLE OF APPLICATION IN ROAD CONSTRUCTION

The analysed section of the expressway is one of the highest traffic load of national roads in the system of transit routes. The aim of the investment is the construction of two roadways with two traffic lanes each, following a new route, with maintaining reserve space for a third lane for the purpose of the future extension which, according to the forecasts, is supposed to take place in 25 years. The length of the constructed road with a concrete pavement is over 32 km in both directions; its structure was composed of a C5/6 20cm and C8/10 20cm road foundation and of 2 layers of pavement and was over 80 cm thick. The concrete pavement intended for the most intensive traffic, KR7, was composed of two layers: the lower one, the layer out of aggregate up to 31.5 mm and 5 cm of the upper layer, out of aggregate up to 8mm, constructed using the exposed aggregate technology.

For the purpose of producing over 200,000 $m^3$ of concrete mix 2 huge mobile production plants were used, with the capability of over 150$m^3$/h each, the mobile production plants were situated at the construction site. In order to produce the assumed amount of concrete mix in a short time, over 300,000 tons of aggregate were gathered on a specially hardened and prepared construction site. The transport of the concrete mix to the concrete paving set was performed using tipper trucks which, at one time, were able to take from 9 to 12 $m^3$ of the concrete mix of the S1/S2 consistency and air content from 4% to 6%. The scale of the undertaking is demonstrated by the fact that the daily production reached 2500 $m^3$ of the concrete mix in the system of continuous work, therefore, it was necessary to plan a supply chain in the form of 40 cement trucks, i.e. over 1000 tons of cement per day. The ordering of the deliveries of particular materials had to take place every day in agreement with the manufacturers of the materials, the carrier and the project manager due to the limited capacity of the cement silos at the construction site.

Fig. 2. Concrete pavement using Wirtgen 1900 with the capability of 800 running meters per day.

The concrete pavement set is Wirtgen 1900 composed of a set of 3 machines for pavement, consecutively, the lower and the upper layer and applying the curing agent. The texturing process was performed mechanically by brushing the upper layer in the time of from 12 to 24 hours from the beginning of pavement process.

The key technological processes which guarantee highest quality standards of the concrete pavement is the process from producing the concrete mix in the mobile production plant through the shortest possible transport time, to paving the mix and appropriate compacting in the structure of the road. In order to face that challenge, the RMCD4.0 delivery system, proposed and described earlier, was introduced. In this system production of the mix for the lower and the upper layer, which differ in terms of composition and parameters, is executed in separate plants/factories. Moreover, the mix for the upper layer was transported using 4-axis tipper trucks which, at one time, take 9 m$^3$, and for the lower layer - using 5-axis trucks with a capacity of 12 m$^3$ of concrete mix. Due to the thickness of the particular layers, the coordinator of the RMCD4.0 system defined the following delivery rhythm: after 3 trucks with the lower layer there was 1 truck with the upper layer - with the use of such a production system there were no stoppages and no problems with the mixing of concrete.

A very important element increasing the flexibility of the time of paving the concrete mix was applying lignosulfonate-based admixtures [32, 43] which increase the plasticity of the mix and stabilize the parameters of the concrete mix in a time of even 90 minutes. The introduced system of the current control of the parameters of consistency and aeration at the concrete batching plant and, at the same time, at the construction site allowed for the flexible management of the properties of the mix depending on the changing transport time and external temperature. In order to increase the accuracy of estimation and, thus, of forecasting the variability of the parameters of the mix depending on external temperature and on the transport distance, every hour a measurement was made of the consistency and air content at both, the producing plants and at the construction site, comparing their change over time. Gathering this knowledge allowed to, on a current basis, introduce all the changes resulting from the theoretical model.

Fig. 3 illustrates the chain links of the supply chain of the concrete mix to the construction site in the analysed case.

A b C d

Fig. 3. The supply chain of the concrete mix to the construction site, a-gathering materials, b-production of the mix at the mobile concrete batching plant , c-concrete pavement, d-concrete curing process.

The beneficial effect of the synergy between Lean Construction and Agile/Flexible Management was achieved thanks to the simultaneous application of real time management compliant with the Construction 4.0 idea. During the implementation of the production process, the transport and road pavement, two cases were analysed which differed in terms of the length of transport and the possibilities to use public roads and technological roads in the area of the construction site:

- Case A - significant transport distance (about 50 km) + arrival via a public road
- Case B - medium transport distance (about 12 km) + arrival via a technical road

In both cases, simulation models were constructed in the WebCyclone software, analysing various technical and organizational variants, in order to maximize the efficiency of the concrete pavement set (WIRTGEN 1900). For each of the cases 3 simulation models were elaborated. They were compliant with the scenarios of simulations which differed, above all, in terms of the transport distance. The simulations associated with case A (A1, A2 and A3) required the application of beta distributions, whereas in case B (B1, B2 and B3) triangular distributions were applied (with the assumption of small deviations of the process implementation time: ±1 minute). In case B, controlling the processes of production, of deliveries and of concrete pavement in real time was applied through constant contact and making decisions between the coordinator and the production manager in accordance with the assumptions of the RMCD4.0 method.

## 5. RESULTS

Two principal cases and three scenarios of deliveries for each of them were analysed:

- Case A: significant transport distance (50±5 km), arrival mostly via public road,
- Case B: medium transport distance (12±3 km), arrival only via technical/service road.
  The simulation provided results that are compliant with the actual course of processes, which has been illustrated in table 3.

Table 3. The results of the simulation of deliveries of ready-mix concrete for cases A and B

| | A1 | A2 | A3 | B1 | B2 | B3 |
|---|---|---|---|---|---|---|
| **Cost PLN/m$^3$** | 36.87 | 35.93 | 34.65 | 14.20 | 14.70 | 15.30 |
| **Efficiency m$^3$/h** | 43.97 | 44.36 | 44.56 | 69.16 | 68.38 | 67.61 |
| **Transport Distance - Km** | 45 | 50 | 55 | 9 | 12 | 15 |
| **The number of concrete mixer trucks** | 22 | 21 | 21 | 6 | 7 | 8 |
| **REMARKS** | | mean | | | mean | |

NB. The cost means the cost of delivering the concrete mix to the construction site (without the production cost)

It is worth to add that the actual number of concrete mixer trucks was:

- From 12 to 22 for case A, the unit cost was on average: 36.45 PLN/m$^3$
- From 6 to 7 (with the assumption of a reserve concrete mixer truck – 1 truck), the unit cost was on average 15.02 PLN/m$^3$.

Observations of the processes which take place at the production plant, associated with the management of the truck fleet, material deliveries and production logistics, using special chemical admixtures as well as during transport and at the construction site confirmed the possibility to ensure significant increase of efficiency in case B, where the coordination of processes was applied in accordance with the assumptions of the RMCD4.0 method. For the simulation model the efficiency increased by 56% which was confirmed in the construction conditions (55%). Thanks to the application of the proposed method RMCD4.0, the process of concrete pavement was significantly improved and ordered. The concrete pavement process was performed without breaks in deliveries, thanks to which it was possible to limit the number of trucks, with the increased efficiency of this process.

## 6. CONCLUSIONS

The presented theoretical bases and simulation calculations as well as experimental measurements allow to draw the following conclusions:

1. The basic problem in the management of the deliveries of ready-mix concrete is the difficulty with achieving compliance between the plan and the actual course of the process, which is the result of, above all, disruptions.
2. While comparing cases A and B it was proven that it is possible to implement a quasi-deterministic model based on real time control on the basis of an appropriate simulation model.
3. The application of Lean and Agile Management resulted in the effect of synergy from the point of view of limiting the influence of disruptions (on one hand, standardizing the times of handling/transport, and on the other – broadening the technological frameworks – the stabilisation of the consistency and of air content in the concrete mix in time passed)
4. Besides the typical transformation model (INPUT-PROCESS-OUTPUT), in the construction process management it is necessary to take into consideration also the FLOW model.
5. This model is based on the synergy of applying Lean Construction and Agile/Flexible Management with ensuring management in real time in accordance with the Construction 4.0 idea.
6. Obtaining the compliance of planning and implementation during the management of the process of deliveries of ready-mix concrete may be achieved by acting in three stages: **planning deliveries** (building a simulation model - choosing the number of concrete mixer trucks etc. to the set efficiency of the concrete paver), **implementation** (a counterpart of the trial section) - verifying the correctness of planning in reality (corrections, if necessary),

**managing the delivery in real time** - putting emphasis on ensuring the stable rhythm of the process of cyclic deliveries of ready-mix concrete - building a quasi-deterministic model.

7. The simultaneous application of the improvement of the process of deliveries of ready-mix concrete with the application of Lean and Agile/Flexible Management is justified by the fact that the too far-reaching introduction of Lean Construction leads to increasing the sensitivity to disruptions (e.g. the weather, an accident at the route of delivery), and Agile/Flexible Management allows to ensure the adjustment to changes. Analogically, a significant increase of applying flexibility may lead to chaos, which is prevented by the simultaneous introduction of Lean Construction.
8. The factors favouring the rhythmical RMC deliveries include: a short transport distance between the concrete batching plant and the construction site, an independent delivery route (e.g. a service road, as in the example B), the possibility to monitor the process in real time and to introduce corrections of current processes - above all: the time of delivery to the construction site.
9. It is, therefore, necessary to suggest the installation of mobile concrete batching plants, which gives the possibility of not only maintaining the stable rhythm of deliveries but also ensures the high quality of the delivered mix.

The authors intend to keep improving the methods of controlling deliveries of ready-mix concrete basing on a systematically supplemented data base, with taking into consideration the specificity of the conditions for each analysed case (learning for cases).

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## LIST OF FIGURES AND TABLES:



## ZWINNOŚĆ/ELASTYCZNOŚĆ I LEAN

## W ZARZĄDZANIU PROCESEM DOSTAW BETONU TOWAROWEGO

Słowa kluczowe: *Zwinność/Elastyczność, Lean, budowa drogi szybkiego ruchu, symulacja, dostawa betonu towarowego, zarządzanie w czasie rzeczywistym*

**STRESZCZENIE**:

Artykuł poświęcony jest metodzie RMCD4.0, która służy zapewnieniu rytmicznych dostaw mieszanki betonowej w oparciu o model quasi-deterministyczny. Opiera się ona na osiągnięciu synergii dwóch metod zarządzania: Lean Construction (której zadaniem jest zapewnienie ograniczenia marnotrawstwa np. czasu podczas załadunku mieszanki betonowej ) i Agile/Flexible Management (zapewnia możliwość dostosowania do zmian ). Istotne znaczenie ma także zastosowanie idei Construction 4.0 – zapewnienie współpracy dzięki komunikacji bezprzewodowej i możliwości lokalizacji urządzeń transportowych w czasie rzeczywistym. Koordynator procesu produkcji, transportu i wbudowania betonu towarowego bazując na modelu symulacyjnym dostaw steruje środkami transportu w sposób zapewniający rytmiczne dostawy mieszanki betonowej w celu osiągnięcia maksymalnej wydajności maszyny wiodącej – zestawu z układarką nawierzchni betonowej.

Teoretyczną podstawą rytmicznych dostaw jest teoria TFV zaproponowaną przez Koskela [31] oparta nie tylko o tradycyjną transformację (T), ale także przepływ (F) i wartość dla klienta (V).

Przedstawiona metoda RMCD4.0 opiera się na trzech etapach:

1. PLANOWANIE (określenie wielkości dostaw na dzień następny – przyjęcie parametrów modelu symulacyjnego);
2. IMPLEMETACJA (dostosowanie modelu do rzeczywistej sytuacji);
3. REGULARNE DOSTAWY BETONU TOWAROWEGO (realizowane są rytmiczne dostawy betonu towarowego z możliwością korygowania sytuacji rzeczywistej przez koordynatora procesu w celu osiągnięcia zgodności z quasi-deterministycznym modelem symulacyjnym).

Naturalnie zaproponowane rozwiązanie zastosować można dla dużych przedsięwzięć budowlanych (betonowanie nawierzchni betonowych, mostów, itp.), kiedy dostawy betonu wymagają wielokrotnego powtarzania (cykliczne procesy budowlane).

Obliczenie symulacyjne wykonano w programie WebCyclone zakładając modelowanie przy przyjęciu modelu probabilistycznego dla przypadku A oraz quasi-deterministycznego dla przypadku B. Jak wykazał omawiany przykład dostaw betonu na budowę nawierzchni drogowej – można osiągnąć znaczący wzrost wydajności procesu produkcji, dostaw i wbudowania betonu towarowego – w granicach 50%. Porównanie przypadków A i B wskazuje na zasadność instalacji mobilnych węzłów betoniarskich – wykorzystanie dróg serwisowych (które realizowane są zgodnie z projektem docelowym i nie generują dodatkowych kosztów) umożliwia dostosowanie tempa dostaw do wydajności maszyny wiodącej – zestawu z układarką nawierzchni.

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