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# OPTIMIZATION OF AGGREGATES SUPPLY FOR CONCRETE PLANTS

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Over the recent years, there is a growing interest in concrete prefabrication. Many of the currently operating concrete plants have implemented systems that increase the quality of manufactured products, have expanded highly automated production lines and have clearly reduced wastes and energy consumption. However, one of the problems often encountered in the construction industry is the inefficient organization of logistics processes. Proper shipments planning of aggregates consisting of the selection of their appropriate quantity and the aggregate stock, corresponding to the needs of concrete plants should contribute to lowering costs. Therefore, it is necessary to carry out the optimization, the aim of which is to minimize costs, as well as to maximize the fulfillment of the degree of expected needs of concrete plants. This paper presents a model that allows purchase strategy optimization of aggregates with different grain size fraction. For research purposes, three separate aggregate stocks and five different concrete plants are considered.

*Keywords*: optimization, concrete plant, aggregates, supply, waste reduction, planning.

## 1. INTRODUCTION

In the last decades, concrete prefabrication has undergone significant transformations. Depending on the region and the country, the reasons for the changes are varied. In the former countries of the socialist economy, the share of prefabricated buildings in the total structure of erected buildings has clearly decreased. In Poland, for example, in 1982, the share of prefabricated construction was over 75% of all constructed structures [1]. Generally, the challenges posed by precast production technologies were related to raising up the production efficiency, shortening the time of performing

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production activities and concrete curing processes, as well as prefabrication deliveries to the right time and place at the construction sites, in accordance with the Just in Time methodology [2].

Nowadays at the global construction market, a wide range of precast elements including, for example, floor and roof beams, slabs, poles, railway slippers, walls and many other elements are offered [3]. The entire construction industry has also undergone major changes, along with increasingly higher requirements in relation to building elements in, among others, dimensional tolerances, thermal insulation. Additionally, the amount of information necessary for construction processes has also increased. Some support came with the introduction of technology radio frequency identification (RFID) and wireless sensor network (WSN), which in the future may play a key role in improving collection and sharing of information in the supply chain process [4,5,6,7,8]. It is also necessary to take into account the changes which the intense development of the Building Information Modelling (BIM), observed in the recent years, brings to precast concrete industry [9,10]. These technologies contribute to the increasing improvement of the Enterprise Resource Planning method (ERP) in concrete precast plants, including the Material Requirements Planning standard (MRP), which is responsible for resource planning in the pre-production phase. Although BIM and RFID enriched Enterprise Resource Planning (ERP) some pragmatic problems still cannot be solved. For example, the mixed production situation, where the production for several projects is carried out in the same plant or even same production line simultaneously, is neglected [11].

In order to maintain the profitability of the concrete plant, it is crucial to implement a proper scheduling as well as the right amount of raw materials supplies, resulting from the current needs of the concrete plant. The problem of using inaccurate planning methods, insufficient resource utilization and overstocking was noticed many years ago [12,13] and, in many cases, is still present. Taking into account the fact that aggregate accounts for about 70-75% of all materials needed in a concrete plant, its purchase has a decisive role. The aggregate stocks price offer differs very often in the size range of grains of aggregate fractions. Considering the different needs of every single concrete plant, resulting from the need to satisfy normative and current stocks, the problem becomes complex. Therefore, it is necessary to develop a tool enabling finding the optimal procurement strategy, minimizing the cost of purchase, while meeting the needs of the concrete plants and taking into account the aggregate stock resources.

## 2. AGGREGATES FOR CONCRETE

Concrete in about 70% of its volume consists of aggregate [14]. Therefore, its properties significantly affect the properties of the concrete mix (consistency, workability and pumpability and bleeding) and hardened concrete (strength, waterproofness, absorbability, frost resistance and abrasion). Properties of aggregates result from the characteristics of the parent rock (density, hardness, strength) and from the applied mechanical treatment in the production process (shape and size of grains, surface texture). When selecting aggregates for concrete, one should be guided by the PN-EN 206 + A1 standard: 2016-12 "Concrete - Specification, Performance, Production And Conformity" [15], taking into account:

- conditions of works implementation,
- use of concrete,
- environmental conditions to which concrete will be exposed (class exposure),
- requirements for exposed aggregate or aggregate used in the case of mechanical treatment concrete surface.

The most important, from the point of view of concrete technology, properties of aggregates are:

- grain composition,
- shape and roughness of grains,
- presence of impurities,
- absorbability,
- strength/abrasiveness,
- frost resistance,
- reactivity (alkaline).

Classification due to the origin of aggregates concrete according to PN-EN 12620 + A1: 2010 [16] is shown in Fig. 1.

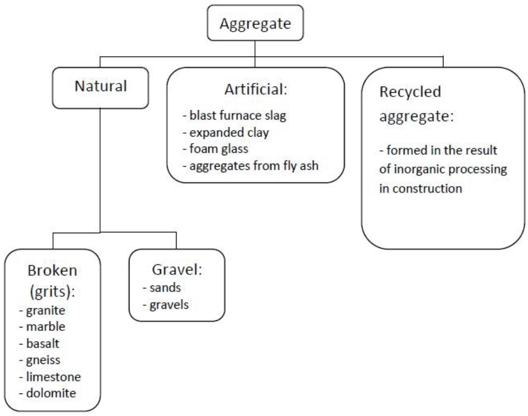


Fig. 1. Aggregate classification

The aggregate mix for concrete should contain several fractions. In order to properly design the mixture the correct proportions of the aggregate should be selected in the concrete thick and sand so that they form a tight pile of concrete detrital. The graining of the concrete aggregate should ensure possibly low demand for cement slurry (cement and water). The main two aggregate features, associated with granulation and water demand that should be minimized, are cavity and external surface. It is not possible, however, to obtain a minimum of these two quantities at the same time. The optimal solution is a compromise, the effect of which is the so-called areas of proper graining. The maximum dimension of aggregate grain in concrete depends on:

- distances between reinforcement bars: usually maximum aggregate grain size cannot be greater than 3/4 of the distance between reinforcing bars;
- dimensions of the element or structure: usually the maximum aggregate grain size cannot be greater than 1/3 of the smallest dimension of the cross-section element.

Another very important feature, next to the size of the aggregate, is the shape of grains. It depends on the type of parent rock and the type of mechanical treatment (broken aggregates). The content of flat and elongated grains above 15% is unfavorable because the water content of the concrete mix increases. Not without significance are also the alkaline reactivity of aggregates and aggregate absorption. The use of aggregates with high water absorption can lead to increased plastic shrinkage.

## 3. OPTIMIZATION OF AGGREGATE TRANSPORTATION

### 3.1. General description

One of the basic problems appearing in the logistics processes of the precast concrete industry is the linking of aggregate stocks with the concrete plants. Concrete plants can be located directly at the precast concrete plants or they can also function as separate production units. The concrete plant's task is to optimize the connections so that the demand for aggregates can be met at the lowest costs of purchasing and transporting them. In this paper, five concrete plants ($i = 1, 2, 3, 4, 5$) were presented to which the aggregate must be delivered from three aggregate stocks ($j = 1, 2, 3$), on which there are five types of aggregates ($k = 1, 2, 3, 4, 5$) with the following grain sizes: 0-2 mm, 2-8 mm, 8-16 mm, 16-32 mm, 0-31 mm. Total purchase and transport costs of the selected aggregate fraction $k$ from the given stock $j$ to the concrete plant $i$ are presented in Table 1.

Table 1. Total purchase and transport cost $a_{ijk}$ of aggregates $k$ from the stocks $j$ and to the concrete plant $i$ [PLN/t]

| | Aggregate fraction *k*: | 0-2 mm | | | 2-8 mm | | | 8-16 mm | | | 16-32 mm | | | 0-31 mm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aggregate stock *j*: | S1 | S2 | S3 | S1 | S2 | S3 | S1 | S2 | S3 | S1 | S2 | S3 | S1 | S2 | S3 |
| Concrete plant *i*: | P1 | 54,0 | 48,0 | 42,0 | 48,0 | 64,0 | 56,0 | 72,0 | 72,0 | 60,0 | 80,0 | 72,0 | 80,0 | 54,0 | 36,0 | 36,0 |
| | P2 | 42,0 | 30,0 | 48,0 | 40,0 | 40,0 | 56,0 | 60,0 | 72,0 | 60,0 | 72,0 | 64,0 | 72,0 | 48,0 | 36,0 | 36,0 |
| | P3 | 36,0 | 54,0 | 30,0 | 64,0 | 72,0 | 48,0 | 108,0 | 120,0 | 60,0 | 72,0 | 72,0 | 80,0 | 48,0 | 48,0 | 36,0 |
| | P4 | 30,0 | 30,0 | 36,0 | 40,0 | 56,0 | 64,0 | 84,0 | 96,0 | 60,0 | 48,0 | 56,0 | 48,0 | 54,0 | 60,0 | 42,0 |
| | P5 | 36,0 | 30,0 | 42,0 | 80,0 | 73,0 | 40,0 | 108,0 | 60,0 | 72,0 | 48,0 | 56,0 | 80,0 | 36,0 | 54,0 | 42,0 |

Considering the conditions presented above, it should be decided how many tons of aggregates should be ordered and delivered to each concrete plant so that the total cost is minimal.

Table 2. Percentage concrete plants demand $i$ for aggregate fractions $k$ [%]

| | Aggregate fraction *k*: | 0-2 mm | 2-8 mm | 8-16 mm | 16-32 mm | 0-31mm |
|---|---|---|---|---|---|---|
| Concrete plant *i*: | P1 | 15 % | 20 % | 30 % | 20 % | 15 % |
| | P2 | 13 % | 17 % | 33 % | 22 % | 15 % |
| | P3 | 18 % | 19 % | 34 % | 21 % | 8 % |
| | P4 | 11 % | 24 % | 26 % | 20 % | 19 % |
| | P5 | 14 % | 18 % | 34 % | 21 % | 13 % |

In addition, the percentage demand for aggregate fractions by the concrete plants, presented in Table 2, should be taken into account. The total resources of aggregates in stocks $j$ account for: S1 = 900 tones, S2 = 2800 tones, S3 = 3300 tones and the total concrete plants $i$ demand for aggregates is following: P1 = 1300 tones, P2 = 1700 tones, P3 = 1800 tones, P4 = 1100 tones, P5 = 1100 tones.

### 3.2. MATHEMATICAL DESCRIPTION OF A CASE STUDY

The research problem described in the paper can be solved by the linear programming method [17] in the following 6 steps (Fig. 2).

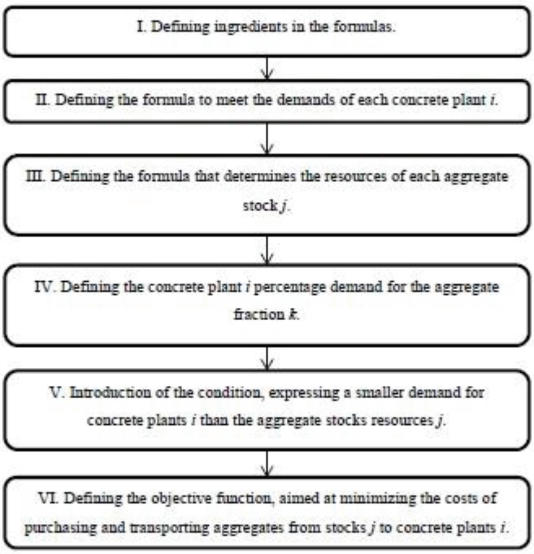


Fig. 2. Proceedings steps for determining the minimum cost of aggregate purchase and transport

Step I includes the following formula ingredients:

$a_{ijk}$ – the total purchase and transport cost of the aggregate unit X of the $k$ fraction from the $j$ stock to the concrete plant $i$.

$b_j$ – the available number of tons of aggregate X on the stock $j$.

$c_i$ – required number of tons of aggregate X in the concrete plant $i$.

$d_{ik}$ – percentage demand of the concrete plants $i$ for aggregates $k$.

$x_{ij}$ – the number of aggregate units X delivered from the stock *j* to the concrete plant *i* (decision variable).

Step II refers to meeting the demands of each concrete plant *i* with the following formula:

(3.1) $$\sum_{i=1}^{5} x_{ij} = c_i, \text{for } i = 1, 2, 3, 4, 5.$$

In Step III the formula that determines the resources of each aggregate stock *j* is following:

(3.2) $$\sum_{j=1}^{3} x_{ij} = b_j, \text{for } j = 1, 2, 3.$$

Step IV concerns concrete plant *i* percentage demand for the aggregate fraction *k* that is expressed by the formula:

(3.3) $$\sum_{k=1}^{5} d_{ik} = 1, \text{for } j = 1, 2, 3, 4, 5.$$

In order to solve this research problem, it is necessary to condition that the concrete plant demands do not exceed the resources of the aggregate stocks, which are expressed in step V as follows:

(3.4) $$\sum_{i=1}^{5} c_i \leq \sum_{j=1}^{3} b_j$$

Finally, in the last step VI, the objective function, minimizing the purchase and transportation cost of aggregates, should be formulated:

(3.5) $$\sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{k=1}^{5} a_{ijk} x_{ij} d_{ik} \rightarrow \text{minimum}$$

wherein $x_{ij} \geq 0, for\ i = 1, 2, 3, 4, 5\ and\ j = 1, 2, 3.$

### 3.3. Results achieved

Using the linear programming the following results were obtained (Tab. 3).

Table 3. The tonnage of aggregates to be ordered from stocks *j* and delivered to concrete plants *i* [t]

| | Aggregate stock *j*: | S1 | S2 | S3 | TOTAL: |
|---|---|---|---|---|---|
| Concrete plant *i*: | P1 | 260,00 | 634,00 | 406,00 | 1300,00 |
| | P2 | 0,00 | 1139,00 | 561,00 | 1700,00 |
| | P3 | 0,00 | 378,00 | 1422,00 | 1800,00 |
| | P4 | 266,00 | 121,00 | 713,00 | 1100,00 |
| | P5 | 374,00 | 528,00 | 198,00 | 1100,00 |
| | TOTAL: | 900,00 | 2800,00 | 3300,00 | **7000,00** |

The total aggregate stock resources are equal to the total demands of concrete plants and amount to 7,000 tonnes. Therefore, condition 3.4 is met. Taking into account the size of the aggregate fraction and the demands of the concrete plants, the optimal tonnage of orders and deliveries is presented in Tab. 4.

Table 4. The tonnage of aggregate fractions *k* to be ordered from stocks *j* and delivered to concrete plants *i* [t]

| | Aggregate fraction *k*: | 0-2 mm | 2-8 mm | 8-16 mm | 16-32 mm | 0-31mm | TOTAL: |
|---|---|---|---|---|---|---|---|
| Concrete plant *i*: | P1 | 195,00 | 260,00 | 390,00 | 260,00 | 195,00 | 1300,00 |
| | P2 | 221,00 | 289,00 | 561,00 | 374,00 | 255,00 | 1700,00 |
| | P3 | 324,00 | 342,00 | 612,00 | 378,00 | 144,00 | 1800,00 |
| | P4 | 121,00 | 264,00 | 286,00 | 220,00 | 209,00 | 1100,00 |
| | P5 | 154,00 | 198,00 | 374,00 | 231,00 | 143,00 | 1100,00 |
| | TOTAL: | 1015,00 | 1353,00 | 2223,00 | 1463,00 | 946,00 | **7000,00** |

The calculation was carried out by means of Microsoft Excel 2013 spreadsheet solver. Non-negative values for unrestricted variables were taken into account during the calculation process.

## 4. Conclusion

The study established proceeding steps in aggregate purchase and transportation procurement from different aggregate stocks to concrete plant, considering optimization in terms of cost. A linear programming was applied to search for an optimal procurement strategy meeting the minimum purchase and transportation costs while limiting the aggregate stocks resources and the concrete plants demand. For experimental purposes, a case study of five concrete plants and three aggregate stocks was used. In addition, aggregates were divided into 5 different fractions: 0-2 mm, 2-8 mm, 8-16 mm, 16-32 mm, 0-31 mm. The optimal strategy of aggregate purchase and transportation taking into account lowest costs is presented in Tab. 5.

Table 5. Minimum aggregate purchase and transportation costs from stocks *j* to the concrete plants *i* [PLN]

| | Aggregate stock *j*: | S1 | S2 | S3 | TOTAL: |
|---|---|---|---|---|---|
| Concrete plant *i*: | P1 | 12480,00 | 34332,00 | 24072,00 | 70884,00 |
| | P2 | 0,00 | 51306,00 | 33660,00 | 84966,00 |
| | P3 | 0,00 | 27216,00 | 68040,00 | 95256,00 |
| | P4 | 10656,00 | 3630,00 | 36402,00 | 50688,00 |
| | P5 | 16236,00 | 27060,00 | 7920,00 | 51216,00 |
| | TOTAL: | 39372,00 | 143544,00 | 170094,00 | **353010,00** |

Finally, the optimized purchase and transportation strategy, including overall and varied percentage of aggregate fraction demands by each concrete plant was obtained with the lowest costs amounting to 353 010,00 PLN. The calculation assumed that variables can only be natural numbers, including zero. The research demonstrates the effectiveness of the adopted assumptions to optimize purchase and transportation of aggregates. Future research directions should focus on developing models combining optimal scheduling for production, internal and external transport as well as planning and further resource allocation strategies with regard to time-cost optimization [18]. It is necessary to consider the variability of conditions under which concrete plants and aggregate stocks are operating. It is strictly related to diversified conditions regarding the supply and demand on the construction market, which affects the level of price volatility. It seems, therefore, necessary to supplement the decision-making and optimization models with a probabilistic-statistical approach. For this purpose, the use of simulation methods to determine orders in variable conditions should also be considered. In addition, a large number of variables and a high level of complexity of these models may necessitate the use of research methods based on metaheuristic algorithms.

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## OPTYMALIZACJA DOSTAW KRUSZYW DLA BETONOWNI

*Słowa kluczowe*: optymalizacja, betonownia, kruszywa, dostawa, redukcja odpadów, planowanie

**STRESZCZENIE:**

Niniejszy artykuł porusza zagadnienie optymalizacji strategii zamówień kruszyw dla potrzeb produkcji mieszanki betonowej w betonowniach. Zagadanie to jest szczególnie ważne w kontekście dużego zróżnicowania cen surowców i materiałów budowlanych występujących na placach składowych i u producentów. Nie bez znaczenia są także zmiany cen i surowców dla budownictwa, które szczególnie w latach 2006-2007 w Polsce wzrosły o ponad kilkadziesiąt procent. Uwzględniając powyższe uwarunkowania oraz perspektywy rozwojowe w budownictwie, w którym beton jest jednym z podstawowych i głównie stosowanych materiałów, należy dążyć do optymalizacji jego procesów wytwórczych. Z jednej strony należy zapewnić spełnienie coraz wyższych wymagań w zakresie technicznym, technologicznym i środowiskowym, z drugiej strony należy dążyć do minimalizacji kosztów jego wytworzenia. Uzyskanie tych celów możliwe jest poprzez optymalizację procesu zamówień kruszyw, które są głównym, pod względem wagowym i objętościowym, jego składnikiem. W tym przypadku należy dążyć do uzyskania wymaganej względami technicznymi i technologicznymi odpowiedniej krzywej uziarnienia, która umożliwi m.in. otrzymanie właściwej urabialności mieszkanki betonowej, uniknięcia problemów z jej pompowaniem, zagęszczeniem oraz segregacją jej składników, zapewnienia możliwie niskiego zużycia cementu, uzyskanie niewielkiej ilości porów w stwardniałym betonie oraz wymaganych normowo parametrów wytrzymałościowych i twardościowych betonu. Nie należy przy tym pomijać aspektów ekonomicznych związanych z zakupem i transportem kruszywa, który istotnie wpływa na opłacalność funkcjonowania całej betonowni. W tym celu w niniejszym artykule zaproponowano zbadanie pięciu betonowni o rożnym zapotrzebowaniu na kruszywo, odpowiednio: 1300 ton, 1700 ton, 1800 ton, 1100 ton i 1100 ton. Każdy z trzech ujętych w obliczeniach placów składowych kruszyw dysponował zapasami w następującej wielkości: 900 ton, 2800 ton i 3300 ton, co stanowiło łącznie wartość 7000 ton. Dodatkowo każda betonownia zgłaszała odmienne zapotrzebowanie na kolejne pięć frakcji kruszyw, tj.:

- frakcja 0-2 mm, betonownia I: 15%, betonownia II: 13%, betonownia III: 18%, betonownia IV: 11%, betonownia V: 14%;
- frakcja 2-8 mm, betonownia I: 20%, betonownia II: 17%, betonownia III: 19%, betonownia IV: 24%, betonownia V: 18%;
- frakcja 8-16 mm, betonownia I: 30%, betonownia II: 33%, betonownia III: 34%, betonownia IV: 26%, betonownia V: 34%;
- frakcja 16-32 mm, betonownia I: 20%, betonownia II: 22%, betonownia III: 21%, betonownia IV: 20%, betonownia V: 21%;
- frakcja 0-31 mm, betonownia I: 15%, betonownia II: 15%, betonownia III: 8%, betonownia IV: 19%, betonownia V: 13%.

Ceny poszczególnych frakcji kruszyw mieściły się w przedziałach:

- frakcja 0-2 mm: od 30 do 54 zł/tonę;
- frakcja 2-8 mm: od 40 do 80 zł/tonę;
- frakcja 8-16 mm: od 60 do 120 zł/tonę;
- frakcja 16-32 mm: od 48 do 80 zł/tonę;

- frakcja 0-31 mm: od 36 do 60 zł/tonę.

W kolejnych sześciu krokach, będących kolejnymi etapami w postępowaniu obliczeniowym zdefiniowano składowe wzorów obliczeniowych, w tym całkowite koszty zakupu i transportu kruszyw, dostępne zapasy surowców na placach składowych kruszyw, potrzeby betonowni, procentowe zapotrzebowania kolejnych betonowni na dane frakcje kruszywa, liczbę ton kruszywa do przetransportowania, wyrażoną zmienną decyzyjną X. W dalszej kolejności sformułowano wzory określające zapotrzebowanie betonowni na kruszywa oraz zapasy poszczególnych placów składowych. Następne dwa etapy objęły sformułowanie wzoru na procentowe zamówienia kruszyw dla betonowni oraz warunek wymagany do rozwiązania problemu optymalizacyjnego, polegający na mniejszym lub równym sumarycznym zapotrzebowaniu betonowi na kruszywo od łącznych zapasów placów składowych. W ostatnim etapie przeprowadzone zostały obliczenia, oparte na metodzie programowania liniowego, których celem było wyznaczenie strategii dostaw kruszyw przy minimalnych kosztach ich zakupu i transportu. W wyniku obliczeń ustalono, że najkorzystniejszą strategią będzie zakup i transport:

- dla betonowni I: 195 ton kruszywa 0-2 mm, 260 ton kruszywa 2-8 mm, 390 ton kruszywa 8-16 mm, 260 ton kruszywa 16-32 mm, 195 ton kruszywa 0-31 mm;
- dla betonowni II: 221 ton kruszywa 0-2 mm, 289 ton kruszywa 2-8 mm, 561 ton kruszywa 8-16 mm, 374 ton kruszywa 16-32 mm, 255 ton kruszywa 0-31 mm;
- dla betonowni III: 324 ton kruszywa 0-2 mm, 342 ton kruszywa 2-8 mm, 612 ton kruszywa 8-16 mm, 378 ton kruszywa 16-32 mm, 144 ton kruszywa 0-31 mm;
- dla betonowni IV: 121 ton kruszywa 0-2 mm, 264 ton kruszywa 2-8 mm, 286 ton kruszywa 8-16 mm, 220 ton kruszywa 16-32 mm, 209 ton kruszywa 0-31 mm;
- dla betonowni V: 154 ton kruszywa 0-2 mm, 198 ton kruszywa 2-8 mm, 374 ton kruszywa 8-16 mm, 231 ton kruszywa 16-32 mm, 143 ton kruszywa 0-31 mm.

Założono ponadto, że wielkości tonażu kruszyw do transportu przyjmować będą liczbami naturalnymi.

Przedstawiony w referacie problem badawczy stanowi punkt odniesienia do dalszych badań, w szczególności z zakresie optymalizacji strategii zamówień komponentów, surowców i półfabrykatów dla wytwórni prefabrykatów w warunkach zmiennych, możliwie blisko opisujących warunki rynkowe w budownictwie. Należy także dokładnie przeanalizować trendy w zakresie rozwoju budownictwa uprzemysłowionego, opartego o wyroby prefabrykowane, zarówno w budownictwie kubaturowych, jak i infrastrukturalnym. Pozwoli to na szczegółowe planowanie procesów optymalizacyjnych prowadzenia zamówień komponentów dla zaplecza zakładów produkcyjnych. Mając powyższe na uwadze, przyszłe potrzeby badawcze uzupełnione powinny być o podejście probabilistyczne, przy wykorzystaniu metod symulacyjnych i algorytmów metaheurestycznych.