

WSPOMAGANIE PROJEKTOWANIA LINII PRODUKCYJNYCH U-KSZTAŁTNYCH METODĄ PROGRAMOWANIA SIECIOWEGO

Władysław ZIELECKI, Jarosław SĘP

Streszczenie: W pracy przedstawiono istotę tworzenia linii produkcyjnych U-kształtnych oraz omówiono ich zalety w porównaniu do linii produkcyjnych jednorzędowych. Na przykładzie zaprezentowano możliwość wykorzystania programowania sieciowego do optymalizacji rozmieszczenia stanowisk roboczych w linii U-kształtnej.

Słowa kluczowe: linia produkcyjna U-kształtna, metoda 3P, programowanie sieciowe

1. Wprowadzenie

W trakcie organizacyjnego przygotowania należy ustalić w jaki sposób tworzone będą komórki produkcyjne wyższych stopni. Możemy wykorzystać do tego celu specjalizację technologiczną lub przedmiotową. Specjalizacja technologiczna polega na tworzeniu komórek produkcyjnych poprzez grupowanie stanowisk roboczych realizujących produkcję tą samą metodą wytwarzania (np. gniazda tokarek). Stosując specjalizację przedmiotową komórka produkcyjna wyższego stopnia powstanie w wyniku połączenia stanowisk roboczych realizujących różnymi metodami wytwarzania operacje technologiczne związane z wytwarzaniem określonego wyrobu. Przykładem komórek produkcyjnych tworzonych z zastosowaniem specjalizacji przedmiotowej są linie produkcyjne będące zbiorem stanowisk roboczych rozmieszczonych na powierzchni zgodnie z zasadą liniowości, czyli w kolejności realizowanych operacji procesu technologicznego. Twórcą linii produkcyjnych wyposażonych w taśmy produkcyjne był Henry Ford, ich zastosowanie pozwoliło znacząco przyspieszyć realizację procesów produkcyjnych poprzez uproszczenie procesów transportu wewnętrznego. Linie produkcyjne stały się podstawą rozwoju produkcji masowej w przemyśle.

Projektowanie linii produkcyjnych dedykowanych do wytwarzania jednego wyrobu nie stwarza większych trudności, ponieważ przyjmują one formę linii jednorzędowej (rys. 1). Problemy pojawiają się wówczas, gdy w linii produkcyjnej będzie wytwarzanych kilka wyrobów. Wówczas podczas projektowania należy zoptymalizować rozmieszczenie stanowisk roboczych minimalizując przemieszczenia zasobów produkcyjnych między nimi. Powstają wówczas linie produkcyjne dwu lub wielorzędowe.

2. Metody optymalizacji rozmieszczania stanowisk roboczych.

Na efektywność pracy komórek produkcyjnych ma wpływ rozmieszczenie stanowisk roboczych, które może być zaprojektowane w oparciu o doświadczenie projektantów lub z wykorzystaniem odpowiedniej metody optymalizacyjnej. Najczęściej stosowanymi metodami optymalizacji rozmieszczenia stanowisk roboczych są:

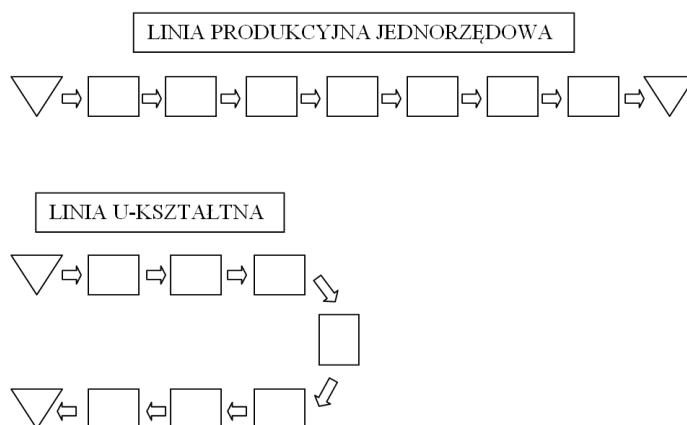
- metoda trójkątów Schmigalli,
- metoda CRAFT,

- metoda CORELAP,
- metoda HC 66,
- metoda programowania sieciowego.

Metody optymalizacyjne pozwalają opracować schemat rozmieszczenia stanowisk roboczych na siatce trójkątów lub prostokątów (kwadratów), który umożliwia opracować projekt rozmieszczenia stanowisk roboczych, w którym uwzględniamy normatywy odległości między maszynami, normatywy odległości maszyn od dróg transportowych i elementów konstrukcyjnych budynków produkcyjnych (ścian, słupów).

Twórcy systemu zarządzania produkcją w koncernie Toyota stwierdzili, że rozmieszczenie stanowisk roboczych w bezpośredni sposób wpływa na realizację transportu wewnętrznego odpowiedzialnego za przemieszczanie przedmiotów pracy, pomocy warsztatowych, materiałów pomocniczych oraz odpadów. Niewłaściwe rozmieszczenie i organizacja stanowisk roboczych powodują wydłużenie tras przewozowych oraz czasu trwania operacji transportowych, wymuszają stosowanie składowania na miejscach odkładczych. Eliminacja tego marnotrawstwa jest możliwa dzięki projektowaniu linii U-kształtnych z wykorzystaniem metody 3P *Production, Preparation and Process* (produkcja, przygotowanie i proces) będącej jednym z narzędzi Lean Manufacturing.

W linii U-kształtnej stanowiska robocze są ustawione blisko siebie w kolejności odpowiadającej sekwencji operacji technologicznych dla danego wyrobu lub grupy wyrobów, a poszczególne części często są przekazywane bezpośrednio z jednego stanowiska do drugiego. Pracownicy znajdują się wewnątrz powstałej komórki. Materiały dostarczane są z zewnątrz, co nie ogranicza ruchów pracowników. Ponadto w linii U-kształtnej mamy krótsze drogi przemieszczania przedmiotów pracy, łatwiejszą komunikację, łatwiejszy wgląd w zapasy produkcji w toku, łatwiejszy kontakt między pracownikami [1].



Rys. 1. Transformacja linii produkcyjnej jednorzędowej do linii U-kształtnej

Metoda 3P w odróżnieniu od innych narzędzi Lean Manufacturing (metody 5S, TPM, SMED, Poka Yoke, Andon, Jidoki) koncentruje się nie na ciągłym doskonaleniu (*kaizen*) lecz wprowadzaniu radykalnych zmian (*kaikaku*) w procesach projektowania i wytwarzania zmian. Polega ona na zaspokojeniu wymagań klienta odnośnie produktu lub procesu poprzez zbiorowe projektowanie i testowanie wielu rozwiązań umożliwiających skrócenie cyklu wytwarzania, zmniejszenie zużycia materiałów oraz zasobów kapitałowych.



Rys. 2. Przykłady makiet 3D projektowanych systemów produkcyjnych [3]

Metoda 3P realizowana jest przez kilka dni etapami, do których można zaliczyć [2]:

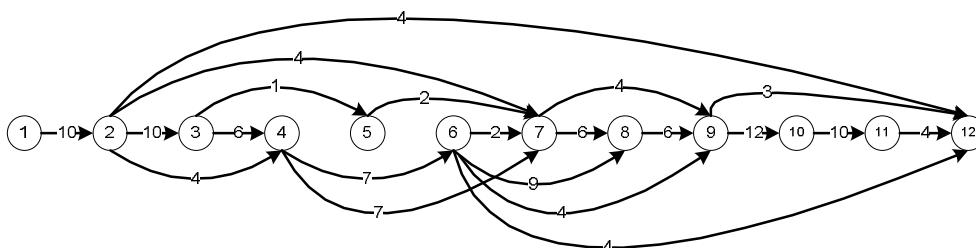
1. Wybór kierownika zespołu 3P, pełniącego również funkcje moderatora dyskusji.
2. Wybór docelowego celu lub obszaru projekt 3P.
3. Wybór interdyscyplinarnego zespołu realizującego projekt, w skład którego powinni wejść: konstruktorzy wyrobu, technolodzy, inżynierowie jakości, inżynierowie ds. produkcji, pracownicy produkcyjni, przedstawiciele służb zaopatrzeniowych i dystrybucyjnych (marketingowych).
4. Szkolenie zespołu.
5. Zbieranie danych o procesie.
6. Określenie kryteriów projektu 3P oraz sporządzenie odpowiednich formularzy.
7. Opracowanie przez każdego członka zespołu indywidualnych propozycji rozmieszczenia maszyn i realizacji procesu.
8. Zebranie zespołu, w trakcie którego dokonywana jest ocena indywidualnych projektów oraz dyskusja nad nimi z wykorzystaniem metod heurystycznych.
9. Wybór trzech najlepszych projektów i budowa makiet przestrzennych (w układzie 3D) wytypowanych projektów, które wykonywane są najczęściej z tektury (rys. 2).
10. Ocena wykonanych modeli w oparciu o przeprowadzone badania potencjalnych przepływów produkcji oraz dyskusja nad nimi z wykorzystaniem metod heurystycznych.

11. Wybór najlepszego projektu i jego korekta z uwzględnieniem uwag sformułowanych w trakcie dyskusji.
12. Opracowanie planu wdrożenia projektu.
13. Rozmieszczanie maszyn na określonej powierzchni z uwzględnieniem opracowanego projektu.

Stosowanie metody 3P pozwala zidentyfikować potencjalne problemy związane z przepływem produkcji na etapie dyskusji na proponowanych rozwiązaniach oraz symulacji procesu wytwarzania na makietach 3D. Reorganizując z wykorzystaniem metody 3P linię produkcyjną przekładni osi tylne w zakładach Volkswagena w Kassel spowodowała wzrost wydajności o 67%, zmniejszenie liczby pracowników o 36% oraz skrócenie czasu przepływu o 76% [3].

3. Optymalizacji rozmieszczenia stanowisk roboczych w linii U-kształtnej

Podczas przekształcania linii produkcyjnej jednorzędowej w linię U-kształtną, można zoptymalizować rozmieszczenie stanowisk roboczych wykorzystując metodę programowania sieciowego. Aby przeprowadzić optymalizację rozmieszczenia stanowisk roboczych w linii U-kształtnej należy przedstawić dotychczasową strukturę produkcyjną w postaci grafu (rys. 3) oraz należy wyznaczyć macierz powiązań transportowych $[s_{ij}]$, określającą masę przewożony zasobów między stanowiskami wyrażoną w tonach, oraz macierz odległości $[l_{ij}]$ (przyjmując uproszczenie, że między węzłami odległość jest równa 1 m).



Rys. 3. Schemat sieciowy linii produkcyjnej jednorzędowej

Dla przedstawionej schematycznie linii produkcyjnej należy wyznaczyć macierz powiązań transportowych $[s_{ij}]$, określającą masę przewożony zasobów między stanowiskami wyrażoną w tonach, oraz macierz odległości $[l_{ij}]$ (przyjmując że między węzłami odległość jest równa 1 m).

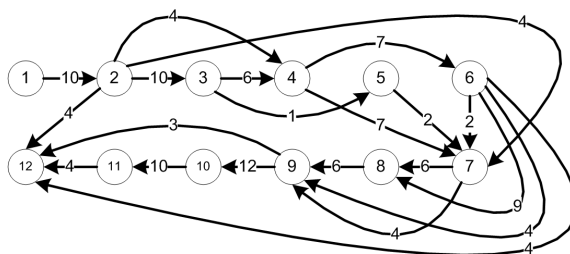
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| - | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| - | | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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W kolejnym kroku należy obliczyć wartość funkcję celu F_c wyznaczaną z zależności 1. Dla rozpatrywanego przypadku funkcja celu uzyskała wartość 232 t·m.

$$F_c = \sum s_{ij} l_{ij} \quad (1)$$

$$F_c = 10 \cdot 1 + 10 \cdot 1 + 4 \cdot 2 + 4 \cdot 5 + 4 \cdot 10 + 6 \cdot 1 + 1 \cdot 2 + 7 \cdot 2 + 7 \cdot 3 + 2 \cdot 2 + 2 \cdot 1 + 9 \cdot 2 + 4 \cdot 3 + 4 \cdot 6 + 6 \cdot 1 + 12 \cdot 1 + 3 \cdot 3 + 10 \cdot 1 + 4 \cdot 1 = 232 \text{ t} \cdot \text{m}$$

Istniejącą linię można przekształcić do linii U-kształtnej bez analizy powiązań transportowych (rys. 4), wyznaczyć macierz odległości $[l_{ij}^{U1}]$ i obliczyć wartość funkcji celu F_c^{U1} – dla analizowanego przykładu wyniosłaby ona 200 t·m (uległa ona zmniejszeniu o 13,8%).

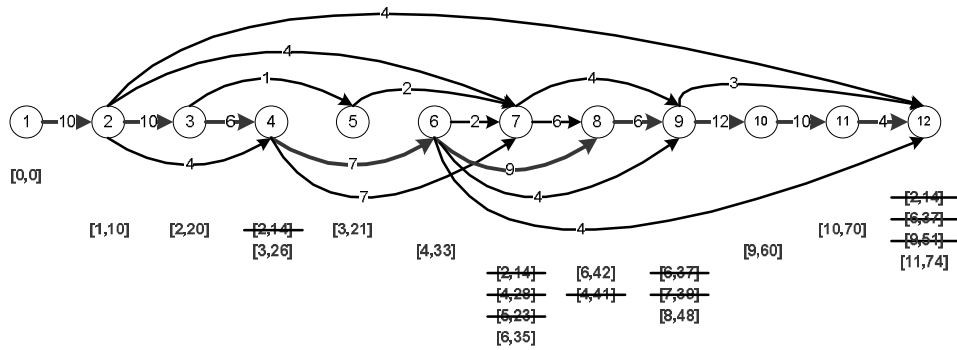


Rys. 4. Schemat sieciowy linii U-kształtnej utworzonej bez analizy powiązań transportowych

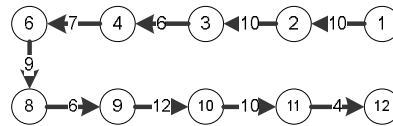
$$[l_{ij}^{U1}] = \begin{bmatrix} - & 1 & 2 & 3 & 4 & 5 & 6 & 5 & 4 & 3 & 3 & 1 \\ - & - & 1 & 2 & 3 & 4 & 5 & 4 & 3 & 2 & 1 & 2 \\ & & - & 1 & 2 & 3 & 4 & 3 & 2 & 1 & 2 & 3 \\ & & & - & 1 & 2 & 3 & 2 & 1 & 2 & 3 & 4 \\ & & & & - & 1 & 2 & 1 & 2 & 3 & 4 & 5 \\ & & & & & - & 1 & 2 & 3 & 4 & 5 & 6 \\ & & & & & & - & 1 & 2 & 3 & 4 & 5 \\ & & & & & & & - & 1 & 2 & 3 & 4 \\ & & & & & & & & - & 1 & 2 & 3 \\ & & & & & & & & & - & 1 & 2 \\ & & & & & & & & & & - & 1 \\ & & & & & & & & & & & - \end{bmatrix}$$

$$F_c^{U1} = 10 \cdot 1 + 10 \cdot 1 + 4 \cdot 2 + 4 \cdot 5 + 4 \cdot 2 + 6 \cdot 1 + 1 \cdot 2 + 7 \cdot 2 + 7 \cdot 3 + 2 \cdot 2 + 2 \cdot 1 + 9 \cdot 2 + 4 \cdot 3 + 4 \cdot 6 + 6 \cdot 1 + 12 \cdot 1 + 3 \cdot 3 + 10 \cdot 1 + 4 \cdot 1 = 200$$

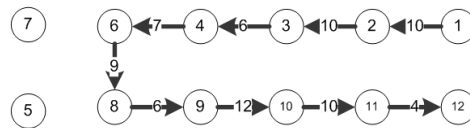
Analizę powiązań transportowych można przeprowadzić metodą programowania sieciowego. Stosując metodę Forda wyznaczamy ścieżkę krytyczną w sieci (rys. 5). Z węzłów leżących na ścieżce krytycznej budujemy linię U-kształtną (rys. 6), a węzły leżące poza ścieżką krytyczną dostawiamy do linii U-kształtnej (w naszym przykładzie z tyłu linii U-kształtnej – rys. 7). Następnie wprowadzamy do sieci linii U-kształtnej brakujące przepływy (rys. 8) i wyznaczamy macierz odległości dla linii U-kształtnej $[l_{ij}^{U2}]$ (zakładany również odległości między stanowiskami są równe 1 m) oraz wyznaczamy wartość funkcji celu F_c^{U2} .



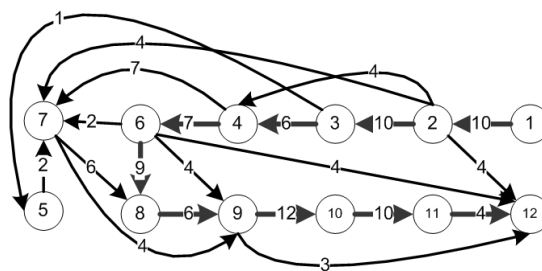
Rys. 5. Ścieżka krytyczna wyznaczona w linii jednorzędowej



Rys. 6. Linia U-kształtna utworzona z węzłów leżących na ścieżce krytycznej



Rys. 7. Linia U-kształtna uzupełniona o węzły leżące poza ścieżką krytyczną



Rys. 8. Model sieciowy linii U-kształtnej po optymalizacji metodą programowania sieciowego

$$[l_{ij}^{U2}] = \begin{bmatrix} - & 1 & 2 & 3 & 6 & 4 & 5 & 5 & 4 & 3 & 2 & 1 \\ & - & 1 & 2 & 5 & 3 & 4 & 4 & 3 & 2 & 1 & 2 \\ & & - & 1 & 4 & 2 & 3 & 3 & 2 & 1 & 2 & 3 \\ & & & - & 3 & 1 & 2 & 2 & 1 & 2 & 3 & 4 \\ & & & & - & 2 & 1 & 1 & 2 & 3 & 4 & 5 \\ & & & & & - & 1 & 1 & 2 & 3 & 4 & 5 \\ & & & & & & - & 2 & 3 & 4 & 5 & 6 \\ & & & & & & & - & 1 & 2 & 3 & 4 \\ & & & & & & & & - & 1 & 2 & 3 \\ & & & & & & & & & - & 1 & 2 \\ & & & & & & & & & & - & 1 \\ & & & & & & & & & & & - \end{bmatrix}$$

$$F_c^{U2} = 10 \cdot 1 + 10 \cdot 1 + 4 \cdot 2 + 4 \cdot 4 + 4 \cdot 2 + 6 \cdot 1 + 1 \cdot 4 + 7 \cdot 1 + 7 \cdot 2 + 2 \cdot 1 + 2 \cdot 1 + 9 \cdot 1 + 4 \cdot 2 + 4 \cdot 5 + 6 \cdot 2 + 4 \cdot 3 + 6 \cdot 1 + 12 \cdot 1 + 3 \cdot 3 + 10 \cdot 1 + 4 \cdot 1 = 187$$

Funkcja celu dla linii U-kształtnej zoptymalizowanej metodą programowania sieciowego, uzyskała wartość 191 t·m i jest mniejsza o 19,4% od funkcji celu linii jednorzędowej. Wskazuje to, że transformacja linii jednorzędowej w U-kształtną spowodowała znaczne zmniejszenie pracochłonności operacji transportowych.

4. Wnioski

Przedstawione w pracy rozważania wskazują na możliwość stosowania metody programowania sieciowego do optymalizacji rozmieszczenia stanowisk roboczych w linii produkcyjnej U-kształtnej.

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Dr hab. inż. Władysław Zielecki, prof. PRz
 Dr hab. inż. Jarosław Sępa, prof. PRz
 Katedra Technologii Maszyn i Inżynierii Produkcji
 Politechnika Rzeszowska
 35-959 Rzeszów; Al. Powstańców Warszawy 8
 tel./fax: (0-17) 865 17 27
 e-mail: wzktmiop@prz.edu.pl
 jsztmiop@prz.edu.pl