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PLANNING ALGORITHMS FOR CYBER-PHYSICAL PRODUCTION NETWORKS IN THE INDUSTRY 4.0 ENVIRONMENT

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Purpose: The paper aims to present the methodology of rapid prototyping of small and medium-sized enterprises' networks operating in the Industry 4.0 environment.
Design/methodology/approach: In the conducted research, the method of literature analysis and mathematical analysis, set algebra, and mathematical logic was used to design algorithms using proposed sufficient conditions, which fulfilment allows for the prototyping of a cyber-physical production network of small and medium-sized enterprises.
Findings: Based on the obtained research results, a general methodology for planning cyber-physical production networks was proposed based on algorithms using a set of sufficient conditions.
Research limitations/implications: The proposed methodology presents only a part of the general model of functioning of the cyber-physical network of enterprises and allows for prototyping of variants of admissible networks. This means the need to integrate the proposed methodology with the planned prototype of e-business platforms, which will be an environment for integrating production companies and potential customers ordering production tasks.
Originality/value: Original achievements obtained during the research include algorithms that allow rapid prototyping of network variants based on available production resources, the cost of their use and transport constraints between companies. Noteworthy is the possibility of obtaining a set of acceptable solutions and choosing the best one due to the cost criterion or the deadline for completing the production order. The proposed approach allows for planning a detailed schedule of production flow, taking into account the load on resources and transport between companies.

Keywords: Industry 4.0, cyber-physical production network, algorithms of networks planning, small and medium enterprises.

Category of the paper: Research paper.

1. Introduction

The fourth industrial revolution is a challenge for the entire economy. It introduces new changes in industry and society (Bauernhansl et al., 2014). The widespread digitization of economic processes forces enterprises to change, especially in using modern communication technologies and building a competitive advantage in the market through intelligent solutions. Combining industrial technologies with modern information and communication technologies (ICT) is the basis of the fourth industrial revolution and the concept of Industry 4.0 (Kagermann et al., 2011). The concept of Industry 4.0 is understood as a combination of intelligent resources and enterprise systems and the introduction of changes in the management of production processes that can increase the efficiency and flexibility of production and guarantee a high level of production personalization (Młody, 2018; Grabowska, Saniuk, 2023). Industry 4.0 builds cyber-physical production systems to integrate information and operational technology in enterprises and supply chains (Lee et al., 2015; Liu et al., 2017).

Today's consumers strongly desire personalized products tailored to their unique preferences and needs (Hu, 2013). As a result, manufacturers must be highly integrated with their clients and involve them in the product development process. This includes offering configurable options for manufactured products and allowing customers to participate in product design. At the same time, customers expect these personalized products to be priced similarly to standard products (Yang, Jun, 2008). To meet this demand for customized products, manufacturers must be flexible and responsive when accepting new production orders. Modern companies must change their business models and focus on developing their product and service offerings. To create additional value for the customer, many companies are adopting a "servitization" or "service infusion" approach, which involves adding services to their standard product offerings (Kowalkowski et al., 2017). Successful companies should focus on developing their know-how and fostering cooperation in today's market rather than solely competing on product offerings. Servitization helps build better customer-producer interaction, better uses resources, and provides networking opportunities (Vargo, Lusch, 2017). This may particularly apply to the sector of small and medium-sized enterprises, which, unlike large enterprises with high development potential, see an opportunity for development in the conditions of Industry 4.0 in cooperation and narrow specialization (Kliment et al., 2021; Adamik et al., 2023).

The idea of a cyber-physical production network means the production order execution within shared intelligent resources of the individual network partners, and communication between resources takes place using real-time data and IoT (Saniuk, 2020). An essential feature of the cyber-physical network is that all network partners have access to the necessary information in real time, regardless of the geographic location of the required resources. Thanks to the direct communication of intelligent resources, partnership development is intensified based on combining essential resources and competencies. Incorporating the help of various enterprises into a network contributes to gaining a competitive advantage in the market and better orientation to the customer's needs (Czakon, 2015). Creating network forms of cooperation is not only an excellent opportunity to produce personalized products and services but also the dynamization of business models as part of the Industry 4.0 concept and an opportunity to increase the competitiveness of enterprises. However, focusing on network services and developing own know-how requires solving several problems resulting from the lack of methods for forming cyber-physical networks of small and medium-sized enterprises (Saniuk and Grabowska, 2021). Hence, research is needed to develop business models and networking concepts that use intelligent resources to implement specific personalized products in customer interaction.

The article's main purpose is to present the methodology of rapid prototyping of small and medium-sized enterprises' networks based on algorithms using the checking of sufficient conditions established to implement personalized production orders.

2. Problem formulation

In the presented case, it is assumed that an e-business platform will be created, bringing together small and medium-sized enterprises equipped with intelligent production resources capable of communicating with the online platform. Enterprises provide information about resources, making them available on the network in real-time. The customer specifies a personalized production order on the e-business platform. Each order specifies the client's expectations concerning the implementation timing and the implementation cost (price).

The production order (project) is understood as a 4-tuple: P = (Z, Ts, Tk, K), where: $Z=\{Zj=(Oj, Lj, ZNj): j\in\{1,..,n\} \wedge$ if $j=1$ then $ZN1=nil$ otherwise $ZNj \neq nil\}$ – a set of tasks belonging to the order P, Ts – the date from which to begin execution of the order, Tk – the date by which the order must be executed, K – the maximum (permissible) price (cost) of the order.

For the description of the order, the following additional indications are set:

Pred(Zj) – a set of predecessors (which deliver their results directly to Zj).

Succ(Zj) – a successor – (which makes use of the results from Zj).

The task is a 3-tuple: Z = (O, L, ZN), where: O – the task description, L – the number of pallets required to transport the task outcome, ZN – an indicator on the another task that directly uses the result of task Z (if the next task for Z does not exist, then ZN = nil).

In the case under consideration, the answer to the following question is sought: *Is there a cyber-physical network of small and medium-sized enterprises that guarantees the timely execution of a production order due to the available production capacity of resources, and the* *total cost of order execution will not exceed the price specified by the client (maximum total cost)?*

Finally, a subset of the enterprise is sought Ω = (F1, …, Fn) set N – enterprises {Fk| k=1, …, N}, which will be able to execute the production order.

The information from intelligent resources of the enterprises will send online as an offer for the task, it means a 5-tuple: OZ = (Z, R, F, Tz, Kz), where:

Z – is a task,

R – the resources needed to complete the task Z,

F – company, where there is a resource R,

Tz – the time required to complete task Z,

Kz – the cost of realization of task Z (the cost includes the total cost of resource use and cost of materials used). Additionally, the enterprise in real-time determines, for each resource, the range of periods accessible to the networks, of which there are three W = (R, T1,T2), where:

R – the resource, [T1,T2] – time interval in which the resource R is available for the e-business platform.

3. Algorithms of cyber-physical networks formation

The proposed methodology for a cyber-physical networks planning is based on a sequence of checking sufficient conditions. The proposed algorithm considers the constraints related to the availability of intelligent resources, the cost of their use, and logistic constraints considering the distance between partners and the cost of transporting components in the physical flow of materials. Three phases can be distinguished in the proposed approach to planning cyber-physical networks. An outline of the methodology is presented in Figure 1.

The first phase, called the "application phase", is the development of a personalized product design and the planning of manufacturing operations (tasks) related to the product's production and delivery to the customer. In this phase, the e-platform customer contacts via the online e-commerce application and specifies the product, selecting the available options and variants regarding the product's shape, size, colour or additional specific features. After the customer specifies the product, determines the implementation date and sends it for implementation, the system will automatically create a plan of production operations by selecting the appropriate production technology and documentation.

In the next phase of the "declaration phase", companies with appropriate resources provide real-time information about the availability of production resources and data related to the costs of their use. The transfer of information in real-time is possible thanks to Industry 4.0 technology Industrial Internet of Things (IIoT), Cloud Computing and Big Data.

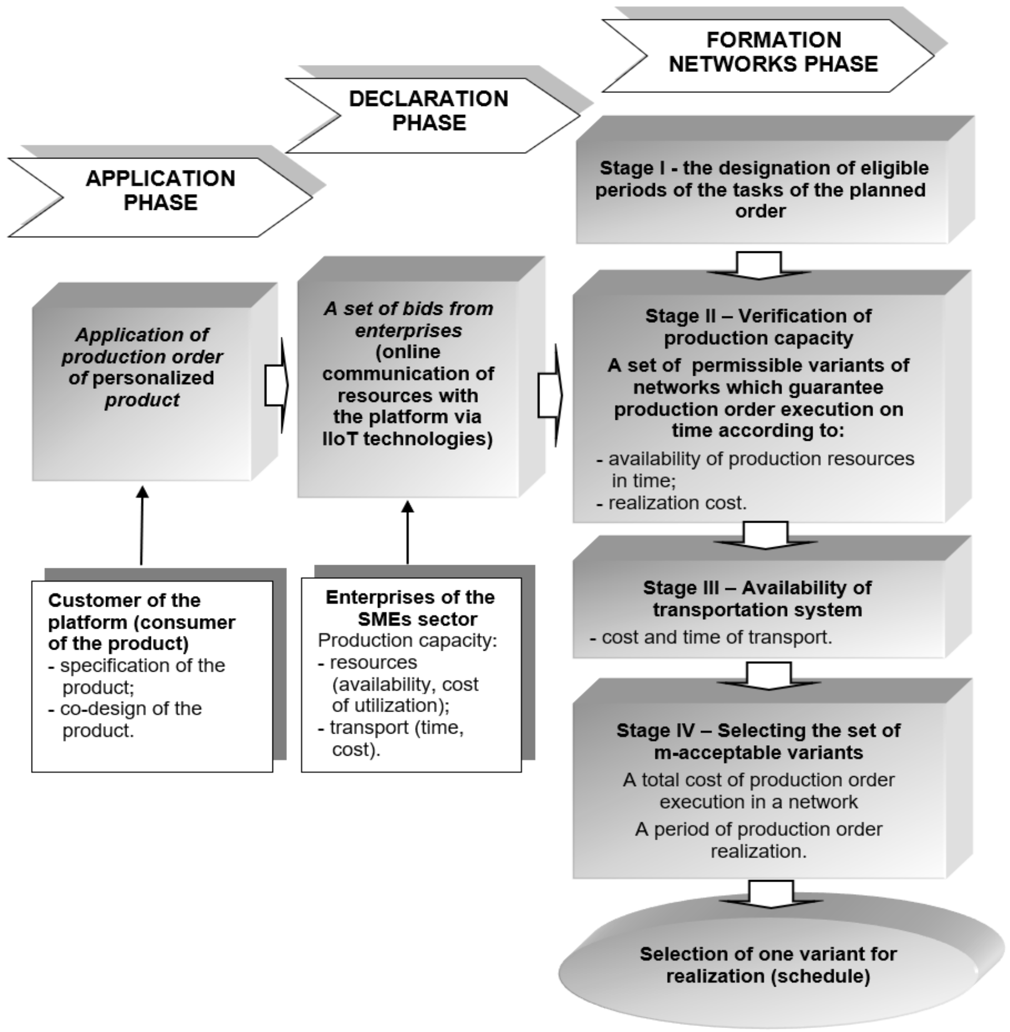

Figure 1. The general scheme of forming a cyber-physical production networks.

In the third phase, multiple network options by carefully selecting production resources and taking into account the logistics involved in transporting materials and components are generated. Then, the expenses associated with fulfilling orders to establish the price of the product are evaluated. Four primary stages of the production network prototyping can be identified in this phase. The first stage is the designation of eligible periods for the implementation of each of the tasks of the planned order based on the submission of tenders in which task durations and the time of execution of transport operations are declared. Upon receipt of all tenders for each information about resources matching the tasks, the number of possible variants of the network can be determined by the formula (1):

$$PDR = \prod_{j=1}^{n} e_{Fj}, \tag{1}$$

where:

e_{Fj} – the number of enterprises offering to performe the *j- th* task,

n – the number of tasks of considered production order P.

The first stage of the algorithm uses DFS (Depth First Search) to designate which individual tasks within Zj can be started earliest (Zj.earliest_start) and which can finish latest (Zj.latest_end), so that the realization of the entire production process of the planned order P is possible in a given period [Ts,Tk].

In addition, the stored value is the lowest offer (Zj.min_cost) and a minimum total cost (Zj.TK) to denote the sum of the minimum cost stated in the bids for all tasks preceding task Zj and minimum transportation costs between the companies, which declared the offer by e-business platform for the tasks Zi and Succ(Zi) after all tasks of Zi, which precedes task Zj. The algorithm to determine the maximum periods of the tasks within the stipulated period of the planned order is shown in Figure 2.

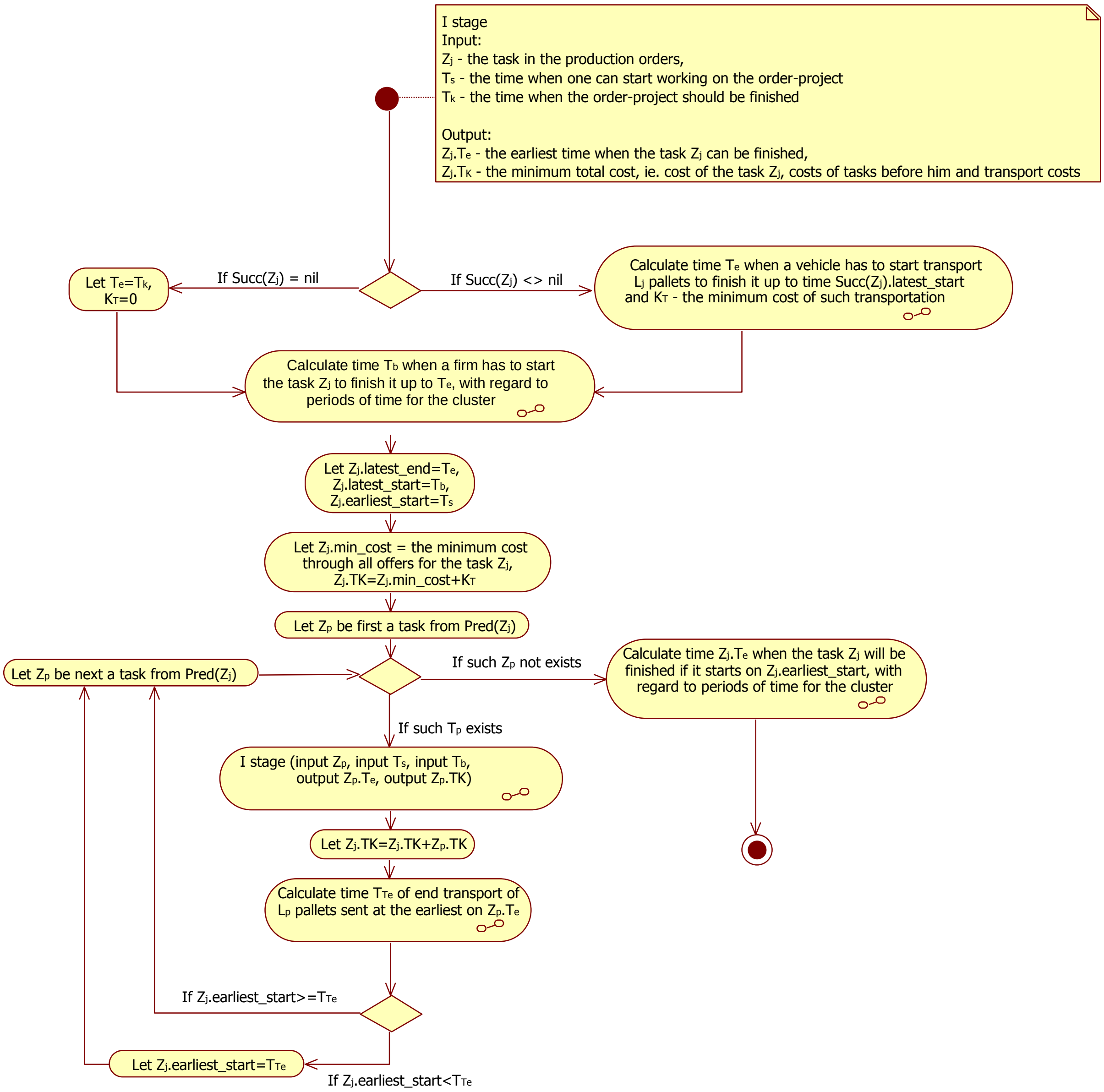

Figure 2. Algorithm of permissible periods planning of task realization.

During the second stage, tenders are allocated to specific periods for completing the task. The number of potential options (PDRI) is then narrowed down by eliminating those that cannot guarantee the availability of resources during designated periods for completing the task. Additionally, any options that exceed the maximum planned cost of the order, including transportation costs, are also eliminated based on the bidder's total cost estimation. Thus, in this stage, all bids for task Zj are eliminated, which cannot be completed within the prescribed time [Zj.earliest_start, Zj.latest_end] and where the declared task completion cost OZ.K is greater than Zj.min_cost+(P.K – Z1.TK).

At this stage, a sufficient conditions check is included (2) and (3), the fulfilment of which ensures that the proposed offer allows the task to be carried out in respect of the stated delivery time for Zj, the transport operation between enterprises, and the availability of the resource R. The following condition (2) must be satisfied:

$$\begin{aligned} &\forall Z_j, \exists OZ_j = (Z, R, F, T_z, D/Time, K_z), \exists W = (R, T_1, T_2), \\ &T_z \le \left| [T_1, T_2] \cap [Z_j.earliest\_start, Succ(Z_j).start - T_{Tj}] \right|, \end{aligned} \tag{2}$$

where:

OZj – the offer made for task Zj,

W – available time of the resource R to realize task Zj,

[T1,T2] – the period of availability of the resource R planned to carry out the task Zj,

Tz – the realization time declared for task Zj,

TRmin – minimum working time of the resource for one task,

TTj – the time required to carry out transport operations between the company OZj.F and the company performing task Succ(Zj),

[Zj.earliest_start, Succ(Zj).start-TTj] – the period during which the task Zj should be completed,

D/Time (Yes/Not) – division of tasks for shorter periods, e.g. in the case of several shorter periods of resource availability.

Similarly, the condition must be that the cost of the task in the offer was accepted. Enterprises with offers, which do not satisfy the condition (3) are rejected.

$$\begin{gathered} r_1 = (P.K - Z_1.TK), \\ \forall Z_j \exists OZ_j = (Z, R, F, T_z D/Time, K_z), \\ OZ_j.K \le Z_j.min\_cost + r_j \text{ and } r_{j+1} = r_j - (OZ_j.K - Z_j.min\_cost) \end{gathered} \tag{3}$$

where:

OZj.K – the declared cost of offers for task Zj,

rj – an amount, which can help determine if the minimum amount for bids for the task Zj, can be increased, not to exceed the budget for the entire order (project) P,

Zj.min_cost – value of the lowest offer submitted for the task Zj,

P.K – the maximum cost (price) of realization of the order P, (Zj.TK) – the sum of the minimum cost stated in the bids for all tasks preceding task Zj and minimum cost of transportation offered for this task, therefore Z1.TK – means the minimum (essential) amount required for the implementation of the order P (assuming that each task should be selected to offer the cheapest option).

Elimination of offerts of enterprises which do not meet such conditions can reduce the number of feasible solutions based on the formula (4) for PDRII.

$$PDR_{I\,I} \leq \prod_{j=1}^{n} e'_{Fj} \, , \tag{4}$$

where:
e'_{Fj} – the remaining number of offers for task Z_j after eliminating offers which do not meet the sufficient conditions for the availability of resources,
n – number of planned tasks for production order P.

In stage III, a set of variants is determined, limited to those that meet the conditions associated with the transport system. Variants in which the transportation cost and delivery time prevent the timely implementation of transport at the given maximum cost of the production order P are rejected. In the proposed approach, it is assumed that an external means of transport is constantly available, along with the possibility of the (optional) use of the enterprise's vehicle. Assessment is subject only to the planned duration of the transport operation between the partners forming the network and the declared cost of the transport. The calculated cost follows directly from a distance between firms and the average rate per kilometre the logistics operator offers in the local market.

In the proposed algorithm shown in Figure 3 for stage II and stage III, the user can restrict the set of feasible solutions sought to a maximum number of variants of expected production networks.

During last stage phase, set of acceptable variants of production networks that represent various resources from different companies are created. Each variant is distinguished by its time and cost of product realization. The customer will choose the final network variant based on these two criteria. Once the customer accepts the price and lead time, the network is formed, and production stages begin in the individual enterprises of the network.

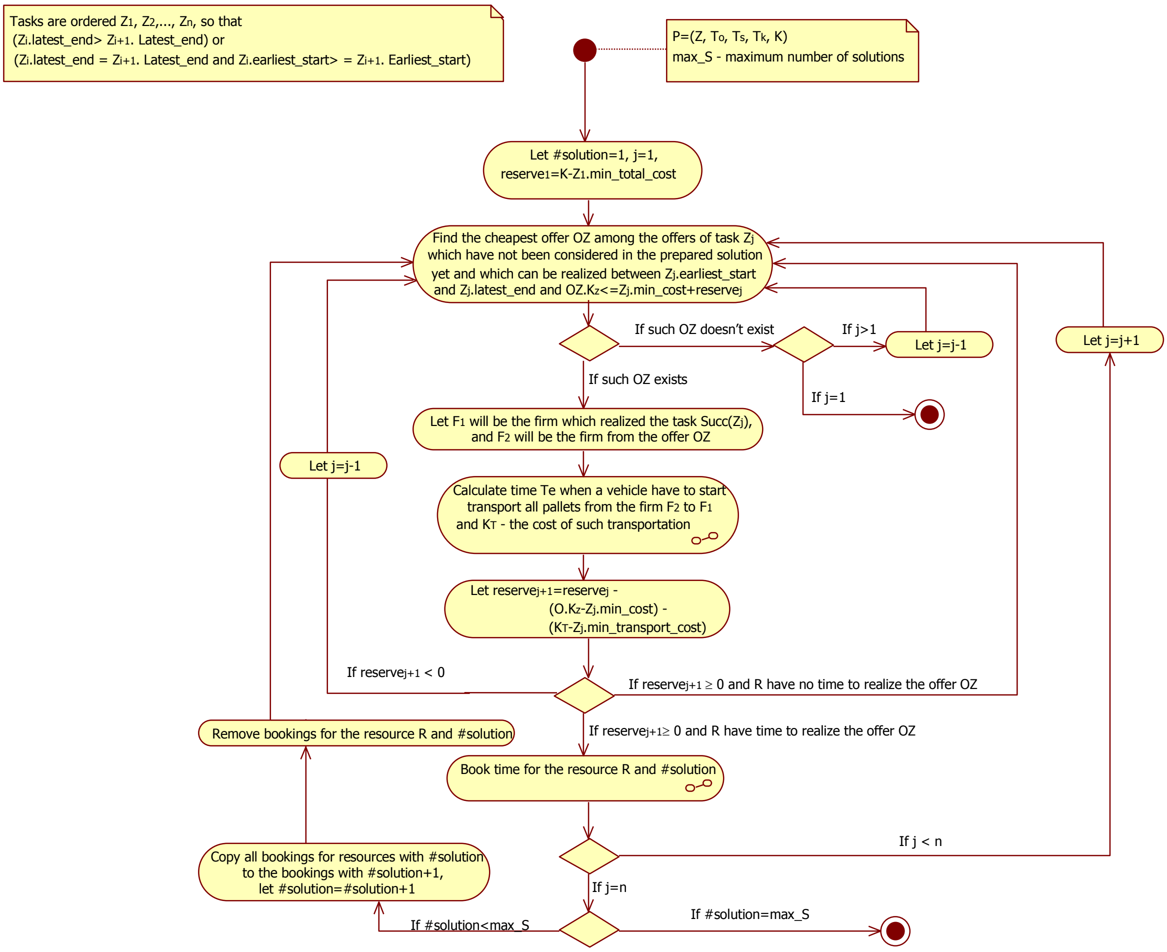

Figure 3. Algorithm for determination of permissible solutions.

4. Discussion and Conclusions

The idea behind Industry 4.0 revolves around seamlessly integrating resources and services offered by different companies involved in production. By adopting servitization, which involves providing additional services along with the core product to enhance customer value, companies can improve their interaction with customers. This approach also allows for optimal utilization of resources and networking opportunities, especially for small and medium-sized enterprises. Unlike large companies, these enterprises can leverage cooperation and narrow specialization for growth in the Industry 4.0 era.

The proposed in the paper sufficient conditions and algorithms for planning a cyber-physical production network of SMEs are an essential element of the model of functioning cyber-physical networks of small and medium-sized enterprises in the Industry 4.0 environment. The methodology allows for the quick generation of a set of acceptable network variants composed of those enterprises whose production capacity proposed guarantees the timely execution of a production order. In the fourth industrial revolution era, we are increasingly dealing with personalized orders that require the specific know-how of various companies. Hence, the organization of e-platforms bringing together specialist companies is an excellent environment for building interaction at the customer-manufacturer level.

The article proposes a prototyping methodology for cyber-physical production networks that can effectively support e-platforms catering to small and medium-sized enterprises. In today's world, customers expect personalized products, and e-business platforms provide a means of integrating customers with manufacturers. Additionally, with the help of the rapid network prototyping methodology, these platforms can also integrate resources (machines, devices, means of transport, employees), and services from small and medium-sized enterprises within the network. By creating cyber-physical networks using this methodology, cooperating companies can increase the utilization of their resources, resulting in improved productivity for network partners.

In the future, conducted research will prioritize the development of an e-platform that can operate within the Industry 4.0 setting. This involves implementing the suggested algorithms and creating innovative business models, particularly tailored to small and medium-sized enterprises that are investing in digital Industry 4.0 technologies.

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