

APPLYING ADDITIVE MANUFACTURING TECHNOLOGIES TO A SUPPLY CHAIN: A PETRI NET-BASED DECISION MODEL

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Nowadays, applying additive manufacturing (AM) technologies into a supply chain (SC) permits realization of the so-called “demand chains” and transformation of conventional production to mass customization. However, integration of AM technologies within an SC indicates the need to support managers’ decision about such an investment. Therefore, this work develops a Petri net-based decision support model that determines the changes in an SC by adopting AM and improving customer-perceived value (CPV), based on a case study regarding a real-life metal production process. The basis for building such a model is the supply chain operation reference model (SCOR), focusing on CPV, due to the need for redesigning the SC starting from the customer instead of the company. To achieve the research objective, this work introduces a novel verification methodology for a Petri net-based decision model. The research results show that applying the developed model, which is based on the selected characteristics of the production process and parameters describing the potential integration of AM within the SC, allows managers to perceive a scenario in the form of graphical models about positive or negative impacts of introducing AM into the SC. The managers find the Petri net-based decision support model presented in this paper a beneficial tool to support the implementation of changes in an SC and show the potential increase in customer satisfaction thanks to the integration of AM within an SC.

Keywords: additive manufacturing technology, supply chain, Petri net, reliability, robustness, decision support system, verification.

1. Introduction

The implementation of additive manufacturing (AM) technology into a supply chain (SC) requires the evaluation of existing approaches supporting the related decision-making process. AM refers to a rapid prototyping technology that manufactures a 3D part,

by laying shapes of material layers (Campbell *et al.*, 2022). Currently, an evident progression is observed for products manufactured using AM technology. It has the great potential to significantly enhance the dynamics of SC, by enabling continuous production of parts without moulding or personalizing them, according to the mass customization strategy. Nowadays, the need for modelling a resilient SC is very important due to possible disruptions

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to it (BCI, 2019). One example was the delay in importing steel and aluminium, in 2018–2019, due to the inability of companies to adjust their custom clearance program (Katsaliaki *et al.*, 2022). However, the application of AM technology to an SC is somewhat uncommon. In the work of Khajavi *et al.* (2014), two aspects of AM technology and SC configuration are presented, namely, the implementation cost of an AM machine and the annual demand assumed. According to Kunovjanek *et al.* (2020), the impact of AM on SC requires the formulation of any future, AM-driven supply chain scenarios. Additionally, production managers are faced with high-level uncertainty to make such a decision (Chen *et al.*, 2023).

According to the literature (Persson *et al.*, 2012; Long, 2016; Ryan *et al.*, 2017) the basis for building such scenarios should be the supply chain operation reference model (SCOR), which is a standard process reference model and consists of processes at three hierarchical levels: (i) process definition (planning, sourcing, making, delivering and returning), (ii) process category (make-to-stock (MTS) products, make-to-order (MTO) products, and engineer-to-order (ETO)), and (iii) the process element and process flows. Our motivation in undertaking this research is one of the directions for future research given by Peng *et al.* (2017), namely, improving the value of the production of in-house AM. Therefore, the main objective of this paper is to analyze and model the impact of AM technology on the SC, focusing on customer-perceived value (the so-called CPV).

According to Zanon *et al.* (2020), CPV is critical in enhancing the SC performance, due to the high correlation between customer satisfaction and market share. To provide managers making decisions about AM technology implemented in an SC, this work has developed a model based on a Petri net, based on an example of metal production. In particular, a model to predict the impact of the integration of AM on the SC in the context of improving CPV is proposed. CPV, in this article, is also considered in accordance with the assumptions of the supply chain operation reference (SCOR) model (SCC, 2017). Modelling these relationships is mostly associated with incomplete or imprecise information. Therefore, to analyze and model such dependencies, Petri nets can be applied through their formal structure. Petri nets are characterized by formalisms and have been successfully tested in hierarchical modeling, analysis and control of distributed systems, which is desirable for SC design and challenging for manufacturing companies in the area of Industry 4.0 requirements (Fierro *et al.*, 2020). Thus, Petri net theory is selected and applied to this decision-making problem (Liu *et al.*, 2017).

Petri nets are a popular graphical way of modelling manufacturing systems (Girault and Valk, 2003). The concurrent nature of Petri nets finds application in manufacturing systems where many tasks can

be performed concurrently (Lee and Seshia, 2016). Flexibility and usability spread the use of Petri nets in modelling systems with different levels of complexity (Bakhtari *et al.*, 2020). Petri nets combine both user-friendly graphic modelling and mathematical notation. Analysis of their main properties is crucial in the context of verifying the reliability and robustness of the modeled system. Especially boundedness and liveness are examined.

Boundedness ensures a finite number of reachable states, since the number of tokens that may appear in a place is finite. Sometimes, such a condition is even more restrictive, and the modelled Petri net ought to be safe (1-bounded) (Best *et al.*, 2001; David and Alla, 2010; Reisig and Rozenberg, 1998). Furthermore, liveness prevents deadlocks in the modelled system (Murata, 1989). Another important issue in the specification of models, or described by Petri nets, is conflict resolution. In this paper, conflicts are resolved by input signals that are assigned to the transitions. Similarly, output signals are associated to places in response to triggering assigned tasks. Such an approach, involving input and output signals, additionally influences the robustness of the modelled system (Patalas-Maliszewska *et al.*, 2022; Majdzik, 2022). In this study an analysis of the literature of AM technology-driven SCs is provided, in order to understand the approaches to integrating AM into an SC. It highlights the main models or methods enabling SC assessment, supported by the performance of AM technology. Secondly, the analysis of the AM-driven SC, within a metal production process, specified as a Petri net is developed.

The main originality of the presented idea relies in the involvement of Petri net theory for designing the changes in production and in SCs due to AM adoption. A detailed description of selected parameters for integrating AM technology into an SC on the example of a production process according to the SCOR model is provided. Next, the system supporting decision making and implementation of AM into an SC is proposed using a Petri net. In particular, an innovative modelling and verification methodology is elaborated. It includes main steps that are required in order to specify and analyze the main properties of the modelled system. Moreover, such a graphical Petri net model enables the visualization of the recommendation of implementing AM technology into an SC in the context of CPV improvement.

The main contributions of this work can be summarized as follows:

- the modelling and verification methodology of a Petri net-based model is elaborated;
- the application of a novel verification methodology of a Petri net-based for designing the changes in an

SC in order to develop a decision support system for production managers is provided;

- the Petri net-based decision support model is illustrated and demonstrated for a real-world case;
- the model for decision support in investment into AM technologies and for designing the changes in an SC by applying Petri net theory is generic and may be adopted in many other manufacturing scenarios;
- the recommendations for managers are formulated and visualized via a Petri net in terms of the expected changes in an SC by adopting AM technologies.

2. Literature review

Applying AM in production can benefit from the versatility of AM machines for resilience improvement (Lupi *et al.*, 2023). Jimo *et al.* (2022) explored the changing state of SC complexities and dependencies, resulting from the adoption of AM technology. Next, they performed an analysis of the implications of competitiveness, and proposed a conceptual framework for configuring AM technology into an SC along with four ways of obtaining information on the interdependencies among the integrated elements. Ekren *et al.* (2023) used the analysis of variance (ANOVA) for statistically significant network model factors to identify the most statistically significant factors, influencing the efficiency of the supply system with the integration of AM technology. Wu *et al.* (2022) analyzed the possibility of locating recycling sites and producing components, using AM, in order to reduce the need for transport and supply components. Their proposed strategic control model connects strategic planning and applies control metrics to relocate overcrowded areas to rural ones. Rinaldi *et al.* (2021), taking into account the huge potential of applying AM technology into an SC, performed an analysis of AM process data, affecting the technological process by using key performance indicators (KPIs). Jimo *et al.* (2019) present approaches based on the illustration of the dynamics of the relationships among elements of the environment, the strategy and organizational structure adopted.

The main benefits of AM adoption in SCs are, among others, the best profit outcomes for the manufacturer (Arbaban and Wagner, 2020), a large number of tasks to be completed in a short time (Yilmaz, 2020), increasing revenues and cost reduction (Dirksen and Feldmann, 2020), reducing production time (Nuñez Rodriguez *et al.*, 2020), improving environmental performance (Sharma *et al.*, 2020) and responding quickly and flexibly to customer requests (Meyer *et al.*, 2021).

Applying a Petri net in decision support systems is a research area that requires further exploration. Saren *et al.*

(2017) deal with the techniques for designing a flexible manufacturing system by using high-level Petri nets. They discuss its modelling and simulation based on hierarchical timed colored Petri nets. Guo and Zeng (2011) propose a control-based design process model by using Petri nets to solve the problems of managing multiple design tasks and a dynamic design process. The model uses decision rules, information places and decision transfer, and fuzzy Petri net theory to describe fuzzy logic and knowledge expression in controlling a design process. The presented approach is tested by using a control instance of a chain conveyor drive system. To find answers and support operators in the design and operation of automated guided vehicle (AGV) systems, a study is conducted using color Petri nets (Yan *et al.*, 2022). A mathematical model is created to study the performance of an AGV system with multiple loads under different scenarios. The results of the study show that failures of AGVs with multiple loads significantly reduce system performance.

Brazález *et al.* (2022) propose a pandemic intelligent transportation system (PITS), based on event processing, fuzzy logic and colored Petri nets, as a response to the restrictions imposed during the COVID-19 pandemic, making it difficult for drivers to reach their destinations. The proposed system uses COVID-19 health indicators to process information about mobility restrictions and create fast routes for drivers. Bulitko and Wilkins (2003) discuss a formalism called time interval Petri nets (TIPNs), which is employed to support qualitative temporal simulation of concurrent processes. They use time intervals in TIPN models, enabling the representation of temporal uncertainty in qualitative simulation.

A qualitative simulator based on TIPNs is developed in the field of ship damage control, replacing an existing quantitative simulator that is too slow (Bulitko and Wilkins, 2003). Condition-based maintenance requires transforming system conditions into a decision-making process, considering financial constraints and energy efficiency goals. An intelligent Petri net algorithm is developed to model and optimize wind turbine operation and maintenance. The method combines Petri net modelling with reinforcement learning and can be used to optimize a Petri net model (Saleh *et al.*, 2023).

The studies regarding developing the decision models in the context of SC designing adopt, e.g., the control theory approach, neural networks, genetic programming, Bayesian networks and Markov processes (Long, 2016). However, modelling the impact of AM adoption into an SC is still underexplored according to Meyer *et al.* (2021).

3. Research questions

There is a research gap in the approach to support decision making in the context of investing in AM technology and

predicting the potential value of in-house AM production. This research is currently being provided to dynamically and quickly meet customer requirements. Considering the role played by AM technology, as applied to SCs, combined with expected close collaboration between producers and customers, the following research questions are formulated: (i) How does AM technology contribute to improving an SC, by focusing on CPV improvement? and (ii) How does integrating AM technology influence the SC and CPV?

Addressing the first question requires identifying parameters of both the production process and characteristics with which the adoption of AM is associated and SC is impacted. Next, the second question is investigated and conceptualized in the form of a Petri net-based decision support model whose implementation allows the presentation of the recommendation of implementing AM technology into an SC.

Our study applies Petri net theory in the development of a decision support model, which determines the changes in the SC by adopting AM. The designed model is firstly specified by an interpreted Petri net. This is an extension of traditional Petri nets by additionally taking into account input and output signals. Such a net ought to be live and bounded. In short, the first property refers to the proper functionality of the system, e.g., avoiding deadlocked states, while boundedness is essential in terms of avoiding improper (unwanted) states of the system.

4. Material and methods

4.1. Manufacturing process with the traditional manufacturing technologies. In order to develop a Petri net-based model for an SC driven by AM technology, the production process for a manufactured metal product is described in detail. It is based on the example of a manufacturing company that produces metal products by using CNC machine tools. The company specializes in unit production and products manufactured in small series. It belongs to the small and medium enterprises (SMEs) sector. The main products are customised ones, assembled from machine-made and ready-made components. For the purposes of the analysis, the following product is adopted: a LED hybrid lamp 40 W HBR-40/400. Its basic technical data is as follows: height: 9 m, light source: 40 W LED, fixture Luminous flux: 4000 lm, lamp working time: up to 15 hours, PV module power: 2×200 W, module dimensions: 1580×808 mm, battery capacity 2×100 Ah and wind turbine power: 400 W. The main objective of this company, in the context of introducing AM into an SC, is to meet production targets, customer requests and distribution within the specified time and at a reasonable cost within production terms.

In cases of this type of production processes,

the production space is usually divided into several production areas, namely, a paint shop, a foundry and grinding shop, etc. The production process with traditional manufacturing technologies takes place on one of the CNC machines where the components of the hybrid lamp shaft are manufactured, together with brackets for the lighting fixtures. Next, the element undergoes quality checks and is sent for assembly with the parts ready, i.e., a wind turbine and a photovoltaic panel. In this case products consisting of three elements are tested: (A) the column shaft with a jib for fitting—an element manufactured in the company on a CNC machine tool; (B) a wind turbine—an element obtained from an external supplier that can potentially be manufactured in the enterprise with the participation of a CNC or AM process and (C) a photovoltaic panel—an element readily obtainable from suppliers.

The current production process is carried out by using CNC machine tools. The material taken from the warehouse, for the production of product A, is delivered to the first operator of the CNC machine, where one of the three components is produced. During the processing of the material, waste is generated and removed by internal transport from the station. The duration of the stage is estimated to be approximately three hours. The product is subjected to quality control by an employee and then sent for assembly. Quality control time is approximately one hour. Component B is transported from the warehouse for further assembly with components A and C. The assembly time is approximately two hours. Component C is a finished product taken from the warehouse and sent for assembly with components A and B. The finished product, consisting of components A, B and C is then transferred to the warehouse for finished products.

4.2. Petri net-based modeling and verification. This section presents an innovative modelling and verification methodology for a Petri net-based decision support model. Firstly, let us formally introduce Petri nets and related notation (Girault and Valk, 2003; Patalas-Maliszewska et al., 2022).

Definition 1. (Petri net) A Petri net N is the quadruple $N = (P, T, F, M_0)$, where P is a set of places, T is a set of transitions, $F \subseteq (P \times T) \cup (T \times P)$ is a set of arcs, M_0 is an initial marking. A state of a Petri net $N = (P, T, F, M_0)$ is called marking, denoted by M . Marking assigns to each place a nonnegative integer $M : P \rightarrow \mathbb{N}$. A marked place $M(p)$ contains at least one token. A transition is enabled if all its input places $\{p \in P : (p, t) \in F\}$ are marked.

Definition 2. (Boundedness) A Petri net is bounded if the number of tokens in every place does not exceed a finite number k for any marking reachable from M_0 .

Definition 3. (Liveness) A Petri net N is live if it is possible to fire any transition from any reachable marking (by a sequence of firings of other transitions).

Definition 4. (Interpreted Petri net) An interpreted Petri net $\mathcal{N}$ is a bounded and live Petri net N that is defined as a 6-tuple $\mathcal{N} = (P, T, F, M_0, X, Y)$. Here X denotes the set of inputs, while Y denotes the set of outputs of the system. In the case of an interpreted Petri net, a transition can fire if and only if it is enabled, and all its associated input values (from the set X) are fulfilled.

Note that several types notation of interpreted Petri nets can be found in the literature. In this paper we assume that an interpreted Petri net specifies a cyber-physical system, and it is bounded and live.

The proposed methodology involves interpreted Petri nets in the modelling of the additive manufacturing system. The discussed methodology (called prototyping flow) involves the following steps:

1. Informal specification of applying AM technologies into an SC.
2. Modelling of the decision support model by an interpreted Petri net.
3. Verification of the model (mainly in terms of liveness and boundedness).
 - If the model is not live and/or not bounded: revise the model—go to Step 2;
 - Otherwise, proceed with the prototyping flow.
4. Further implementation of the decision support model.

Let us briefly explain each of the above steps. Firstly, an informal specification of the production process with the traditional manufacturing technologies and AM ones is defined. Next, the characteristics of the improvements in the SC within the production process are analysed, along with traditional manufacturing, and AM technologies are formulated. Once the system is described informally, it is modelled by an interpreted Petri net. According to the presented requirements (Definition 4), such a description additionally involves input and output signals. They are used for communication with the environment, e.g., inputs are usually employed to pass conditions to the system, while outputs contain the results. In our assumptions, inputs are associated to transitions, while outputs to places of an interpreted Petri net.

The subsequent step refers to the verification of the Petri net-based specification. This is a crucial phase of the proposed flow, since it permits us to detect errors at the early-prototyping stage. According to Definition 4, such a system ought to be live and bounded. Therefore, beside the modeling of the system, verification of such properties

is a crucial step in the presented methodology. Moreover, validation of the system may be also considered. Note that those terms are often confused. Nevertheless, according to the IEEE standard 1012 (Coronato, 2018), verification relates to the checking whether the specified system fulfils the requirements, while validation refers to the examination whether a right system is prototyped. In our flow, we focus on the verification aspects of a Petri net-based system. In particular the examination of liveness and boundedness of the system is considered.

Note that particular verification techniques are out of the scope of this paper, while their detailed description can be found in our previous papers (Wiśniewski *et al.*, 2023a; 2023b). Nevertheless, there exist several techniques that allow us to perform such verification. Let us just briefly summarize two most popular methods. One is based on reachability graph exploration (analysis of the reachable states in the system) (Li *et al.*, 2020; Huang and Zhou, 2020; Su *et al.*, 2023; Qi *et al.*, 2023) while the other involves a linear algebra technique and computation of place and/or transition invariants (Yu *et al.*, 2018). A detailed description of both the ideas can be found in the works of Wiśniewski *et al.* (2023a) and Wojnakowski *et al.* (2021). Here we focus directly on the popular mistakes and errors that may occur in the system. Therefore, let us discuss the most common ones. Firstly, we will analyze the liveness of a system, and then we will move on to the boundedness property.

Assume a system specified by an interpreted Petri net shown in Fig. 1(a). It consists of three places: $P = \{p_1, p_2, p_3\}$ and three transitions: $T = \{t_1, t_2, t_3\}$. There are two input signals: $X = \{x_1, x_2\}$, and three output signals: $Y = \{y_1, y_2, y_3\}$. Let us analyze its behaviour. Initially, place p_1 is marked. This means that potentially (without considering input signals) either t_1 or t_2 can fire. Note that signals x_1 and x_2 are disjoint and cannot be set at the same time: if x_1 is active, t_1 may fire, while activation of t_2 involves the firing of t_2 . The presented situation is a typical conflict in a Petri net (transition t_1 or t_2 may fire). However, usage of the interpreted Petri net with additional input signals permits resolution of the conflict (Gomes, 2005; Gomes *et al.*, 2007; Wiśniewski, 2021). Firing t_1 moves a token from p_1 to p_2 , as shown in Fig. 1(b). Alternatively, firing t_2 moves a token from p_1 to p_3 , as presented in Fig. 1(c). Regardless, of which transition fires, the system is deadlocked, and t_3 cannot fire. In the situation represented by Fig. 1(b) there is a token in p_2 , but there is no token in p_3 . Similarly, in Fig. 1(c) there is a token in p_3 , but none in p_2 . This means that the system is not live and it should be corrected. A possible revised version is shown in Fig. 1(d). The revised version of the system includes additional transition (t_4), and it is connected with an incoming arc from p_3 . Its outgoing arc is connected to p_1 . Thanks to such a modification there is no deadlock

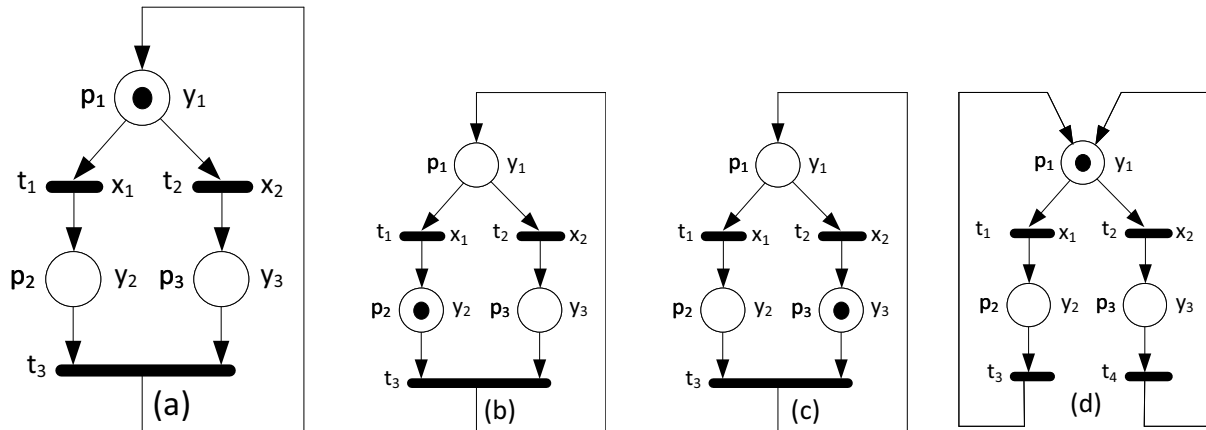


Fig. 1. Sample net that is not live: initial version (a), after firing t_1 (b), after firing t_2 (c), modified version (d).

in the system, and it is live.

Assume a system specified by an interpreted Petri net shown in Fig. 2(a). It consists of three places: $P = \{p_1, p_2, p_3\}$ and three transitions: $T = \{t_1, t_2, t_3\}$. There is one input signal: $X = \{x_1\}$ (assigned to t_1) and three output signals: $Y = \{y_1, y_2, y_3\}$ (associated to p_1 , p_2 , and p_3 , respectively). The system behaves as follows. Once x_1 is active, t_1 is enabled and it may fire. Firing such transition removes a token from p_1 to p_2 and p_3 , as shown in Fig. 2(b). Note that in this marking two places, p_2 and p_3 , are marked. Moreover, operations associated with them (y_2 and y_3) are executed at the same time (concurrently). Such a possibility of concurrent operations is one of the huge benefits of Petri net-based systems. Further firing of t_2 returns a token from p_2 to p_1 . Similarly, firing t_2 moves a token (from p_3) to p_1 as well. Clearly, depending on the timing of transaction firings, two tokens can be accumulated in p_1 . Further execution of the system results in infinite accumulation of tokens, since they increase at each firing of t_2 and t_3 . According to Definition 2 such a situation means that the system is not bounded and it should be corrected. The revised version is shown in Fig. 2(d). Note that t_3 was removed from the system, while t_2 joins both incoming arcs: from p_2 and p_3 . In the revised system, firing t_2 consumes tokens in both places (p_2 and p_3) and puts one token in p_1 , and the system is bounded.

Finally, the last step involves implementation of the modelled and verified Petri net-based decision support model that enables receiving the scenario in the form of graphical form about possible, positive or negative impacts of introducing AM into an SC based on the formulated parameters (Factors 1–4). Next, managers can then make their decisions in terms of the expected changes in SC by adopting AM technologies. Let us now explain the presented flow with a real-life manufacturing process with the adoption of AM is associated.

5. Results

5.1. Informal specification: Assumptions for the Petri net-based decision support model. In order to identify characteristics of the discussed production process with which the adoption of AM is associated, based on a real-life case study, we first specify the production process by considering the possibility of implementing AM technology and supporting the production process, while reducing the amount of waste material and the involvement of employees operating the CNC machine and performing quality control. Materials taken from the warehouse for the production of component B are transported to the second CNC machine tool, where the components of component B are produced.

It is assumed, at this stage, that implementation of an AM machine can support the production of component B by completely replacing the CNC machine, or it can also support the production process by co-production with component B of the CNC machine. Elements of component B produced on CNC and AM are subject to quality control and then assembled onto component B, which is sent for further assembly with components A and C. In the case of the production of component B alone on an AM machine, B is ready to be handed over for assembly with components A and C. Therefore, to model the possibilities for improving the SC's CPV according to the SCOR model, the following SC parameters, within our production process, along with traditional manufacturing and AM technologies for metal products are defined (Wulandari et al., 2023):

- Responsiveness is decided via Factor 1: Speed in scheduling the production planning process understood as the values of the parameters (product design time, time taken up in analyzing the production possibilities for the designed product and the planning time taken up in the production process)

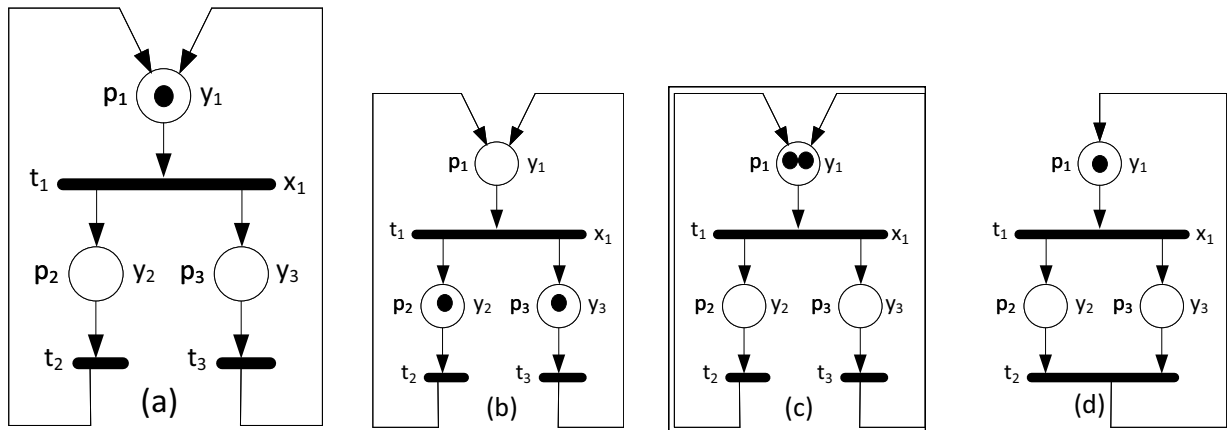


Fig. 2. Sample net that is unbounded: initial version (a), after firing t_1 (b), after firing t_2 and t_3 (c), revised version (d).

and Factor 2: Speed in identifying the requirements of the production process, understood as an analysis of the following parameter values: the number of machines, the number of materials (types), and the number of employees.

- Agility is decided via Factor 3: Speed in determining the raw materials needed to be purchased, understood as the values of the following parameters: the number of suppliers and the availability of materials (1: low availability, 2: medium availability, 3: high availability).
- Reliability is decided via Factor 4: Time required in the delivery schedule, understood as the values of the following parameters: delivery time by individual suppliers, and results expected being the assessment of costs and SC management.

The main characteristics with which the adoption of AM is associated and the SC (Factors 1–4) is impacted are formulated in order to model possibilities to improve the SC of CPV in the following areas: reliability, responsiveness and agility, according to the SCOR model, to find the answers to the questions: Which production processes, in the characteristics of metal products, determine CPV? How can AM be successfully applied to an SC? How can AM know-how be shared in the case of customer co-creation? What are the impacts of introducing AM into the SC of CPV? What is the role of an end-consumer in SC? Therefore, the following assumptions about a Petri Net-based decision support model are made.

Responsiveness: Factor 1 (T_1). Speed in scheduling production,

$$T_1 = \frac{T_1P}{T_1A}, \quad (1)$$

where T_1P = product design time in the production process with traditional manufacturing technologies

+ time taken to analyze production possibilities for the designed product in the production process with traditional manufacturing technologies + time to plan the production process with traditional manufacturing technologies, T_1A = time of product design in the production process with traditional manufacturing and AM technologies + time taken to analyze production possibilities for the designed product in the production process with traditional manufacturing and AM technologies + time taken to plan the production process with traditional manufacturing and AM technologies.

Responsiveness: Factor 2 (T_2). Speed in identifying the production process,

$$T_2 = \frac{T_2P}{T_2A}, \quad (2)$$

where T_2P = the number of machines in the production process in traditional manufacturing technologies + number of materials (types) in the production process in traditional manufacturing technologies + number of employees in the production process, in traditional manufacturing technologies + time taken to plan the production process in traditional manufacturing technologies only if $T_1 > 1$, T_2A = number of AM machines in the production process of traditional manufacturing and AM technologies + number of materials (types) for AM + number of employees for AM + time taken to plan the production process in traditional manufacturing and AM technologies only if $T_1 > 1$.

Agility: Factor 3 (T_3). Speed in determining the raw materials needed. The algorithms take into account only suppliers selected for the implementation of specific orders for materials from the portfolio of suppliers at the company's disposal,

$$T_3 = \frac{T_3P}{T_3A}, \quad (3)$$

Table 1. Input signals assignment to transitions.

Transition	Input	Condition
t_2	x_1	$T_1 \leq 1$, where $T_1 = \frac{T_1 P}{T_1 A}$
t_3	x_2	$T_1 > 1$, where $T_1 = \frac{T_1 P}{T_1 A}$
t_4	x_3	$T_2 \leq 1$, where $T_2 = \frac{T_2 P}{T_2 A}$
t_5	x_4	$T_2 > 1$, where $T_2 = \frac{T_2 P}{T_2 A}$
t_6	x_5	$T_3 \leq 1$, where $T_3 = \frac{T_3 P}{T_3 A}$
t_7	x_6	$T_3 > 1$, where $T_3 = \frac{T_3 P}{T_3 A}$
t_8	x_7	$T_4 \leq 1$, where $T_4 = \frac{T_4 P}{T_4 A}$
t_9	x_8	$T_4 > 1$, where $T_4 = \frac{T_4 P}{T_4 A}$
t_{21}	x_9	$R > 0.25$
t_{19}	x_{10}	$R = 0.25$
t_{23}	x_{11}	$R > 0.75$

where $T_3 P = \sum_{i=1}^k s_i + \sum_{i=1}^n m_i$, $T_3 A = \sum_{i=1}^m s_{AM_i} + \sum_{i=1}^p m_{AM_i}$ and s_i is the number of the k -th suppliers, m_i is the availability of the n -th materials, s_{AM_i} is the number of the k -th AM suppliers, and m_{AM_i} is the availability of the n -th AM materials, where $k, n, m, p \in \mathbb{N}$.

Availability takes the following values:

- 1: low availability (delivery taking over one month)
- 2: medium availability (delivery from two weeks to one month)
- 3: high availability (delivery within two weeks).

Availability is determined considering the delivery time and the enterprises' requirements to complete orders.

Reliability: Factor 4 (T_4). Time required in the delivery schedule,

$$T_4 = \frac{T_4 P}{T_4 A}, \quad (4)$$

where $T_4 P = \sum_{i=1}^k sdt_i$, $T_4 A = \sum_{i=1}^m sdt_{AM_i}$ and sdt_i is the delivery time of the k -th suppliers, sdt_{AM_i} is the delivery time of the k -th AM suppliers, where $k, m \in \mathbb{N}$.

The identified parameters (Factors 1–4) impact the SC because their use enables the accurate determination of the time required for production planning and execution. Moreover, the selected Factors 1–4 allow CPV to be improved through monitoring the reducing product lead time and appropriate use of resources.

5.2. Modelling of a decision support model for applying additive manufacturing technologies into supply chains. The discussed decision support model for

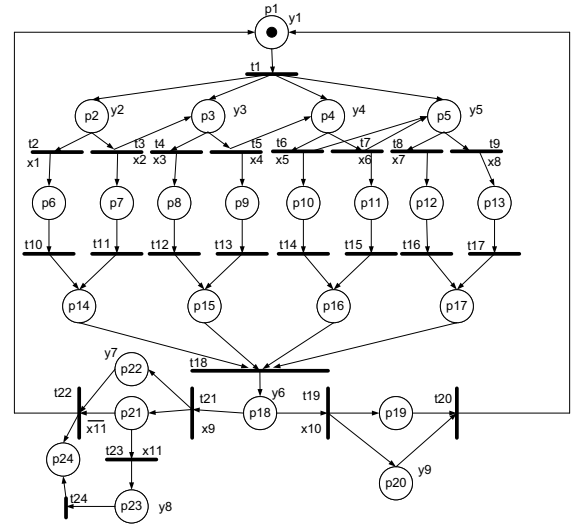


Fig. 3. Initial Petri net-based model of an AM technology-driven SC.

applying AM technologies into an SC is initially specified by an interpreted Petri net shown in Fig. 3. There are 24 places, 24 transitions with 12 inputs and nine outputs signals assigned respectively to transitions and places of this Petri net. Moreover, place p_1 is initially marked by one token.

Tables 1 and 2 outline the relationships between outputs and transitions within the system model. Note that it is assumed that either x_1 or x_2 are active (conditions related to them are disjoint). All the remaining places and transitions in the Petri net (that is, those that do not have an input/output value assigned) are used for assuring the proper functionality of the system. For instance, places p_{14} , p_{15} , p_{16} , and p_{17} are used for proper synchronization of the system.

5.3. Verification of the Petri net-based decision support model. According to the proposed prototyping flow, the subsequent step involves verification of the modelled system. The presented interpreted Petri net is specified with the PIPE (platform independent Petri net editor) (Dingle et al., 2009). Although this tool includes several verification techniques (such as reachability tree-based boundedness and deadlocks analysis), it is not able to check the system. Examination of its main properties (boundedness, deadlock-freeness) fails due to the lack of response, and the tool is not able to compute results within two hours. Therefore, the system is verified with the authors' own tool Hippo (Wiśniewski et al., 2023a). In particular, unbounded areas in the system are searched, according to the technique shown by Wiśniewski et al. (2023b). The tool yields results that the system is not incorrectly specified, by indicating the

Table 2. Output signal assignment to places.

Place	Output	Task
p_1	y_1	Input parameters
p_2	y_2	Speed in scheduling the production
p_3	y_3	Speed in identifying the production process
p_4	y_4	Speed in determining the raw material needed
p_5	y_5	Time required in the delivery schedule
p_6		Print information: Result of speed in scheduling the production is < 1
p_7		Print information: Result of speed in scheduling the production is > 1
p_8		Print information: Result of speed in identifying production process is < 1
p_9		Print information: Result of speed in identifying production process is > 1
p_{10}		Print information: Result of speed in determining the raw material needed is < 1
p_{11}		Print information: Result of speed in determining the raw material needed is > 1
p_{12}		Print information: Result of time required in the delivery schedule is < 1
p_{13}		Print information: Result of time required in the delivery schedule is > 1
p_{18}	y_6	$R = T_1 + T_2 + T_3 + T_4$
p_{22}	y_7	AM technology application into production process is not strongly recommended
p_{23}	y_8	AM technology application into production process is strongly recommended
p_{20}	y_9	AM technology application into production process is not recommended

unbounded places. For example, firing t_3 leads to the unsafe place p_3 . This place may contain more than one token. Furthermore, Hippo suggests problems with the recommendation area (below place p_{18}).

The revised version of the system is shown in Fig. 4. The corrected areas are denoted using the dashed line. The set of additional places and transitions (p_{25} to p_{33} , t_{25} to t_{30}) assures proper synchronization and functionality of the Petri net-based model. Note that the newly added places and transitions ensure boundedness of the Petri net. Furthermore, in order to avoid conflicts in the system, the condition for transition t_{21} (signal x_9) is modified to $R > 0.25$ and $R \leq 0.75$. Thus, only one of the transitions t_{19} , t_{21} , t_{23} can be fired at a time. Let us explain the main modifications in more details through a portion of the modelled system. In the initial version (recall Fig. 3), there are feedback arcs leading from transitions t_3 , t_5 and t_7 to places p_3 , p_4 and p_5 , respectively. Such connections make those places unbounded, and thus they ought to be corrected. Therefore, in the revised version (Fig. 4), such feedback is constructed via newly added transitions (t_{26} to t_{30}). Furthermore, the proper functionality of the system is assured by additional internal places (p_{26} and p_{33}). Also, the area related to places p_{18} to p_{25} is recommended to be rebuilt in order to meet the required assumptions. This time, verification via the PIPE is possible. It concludes that the system is live and bounded. Interestingly, the tool is now able to compute results within a fraction of seconds. This may lead to the very interesting deduction

that the main problems with verification are caused by improperly modelled systems. Let us also note that Hippo confirms proper specification of the revised version as well.

The Petri net model for analyzing the results of the production process with traditional manufacturing and AM technologies assumes that, for the value of $T \leq 1$, the zero value is the result of a negative change, and for $T > 1$ it assumes the value of 0.25, which is the result of a positive change. Depending on the result of the analysis of the parameters, determining the influence of the integration of AM technology with an SC as $R = T_1 + T_2 + T_3 + T_4$, the model generates one of three recommendations for AM technology application to production processes:

- $R = 0.25$: AM technology application to production processes is not recommended;
- $R > 0.25$: AM technology application to production processes is not strongly recommended;
- $R > 0.75$: AM technology application to production processes is strongly recommended.

Applying this model (Fig. 4) allows checking by simulation if the decision on whether the SC is CPV can be improved according to the SCOR model. We have found answers to the first research questions. The question is dependent on the results of analyzing parameters, determining the influence of the integration of AM

technology on the SC: T_1, T_2, T_3, T_4 . The second question is answered in the form of an innovative decision support model (Fig. 3), which allows three recommendations to be established for production managers, in accordance with the SCOR model, i.e., the defined characteristics of the production process of metal products (Fig. 2), regarding the demand for AM technology into an SC.

There is still the unanswered question about the role of the end-consumer in the SC, according to the SCOR model. This is a research area for our future work on how to determine such dependence on incomplete or imprecise information, regarding product co-design and the application of Petri net theory to this decision-making problem.

6. Discussion and implications

The results obtained in the form of the Petri net based model, supporting the decision of a supply chain, driven by AM technology indicate that the new idea presented in this article is useful in practice.

The model enables the analysis of the areas of speed in scheduling production planning, speed in determining the production process, speed in determining the required raw materials, and time required in the delivery schedule

by taking into account the parameters of the machining process and AM technology. On the basis of the analysis, the model generates three recommendations in the area of AM technology implementation, taking CPV into account. The use of the model in business practice can support the decision-making process in the area of analysis of the technology used or the search for a new technology, adaptation and evaluation. However, this study has some limitations. In this article, we worked on a decision support model, based on selected indicators describing incomplete or imprecise information about improvements to an SC's CPV. A limited number of analyzed parameters determines recommendations for the implementation of the new technology. The analytical solution obtained does not give a full picture of further research in order to produce results, including the parameters of the manufacturing process, specified for a given technology.

Further work should include expanding the list of such indicators and conditions, in order to extend the decision model. Secondly, other characteristics of a production process for which the decision-making model is being built are to be analysed.

Currently, the challenge defined by Akbari (2023) is applying AM into an existing SC, and there is still a need for elaborating tools supporting such decisions. The Petri net-based decision support model presented in this paper can be treated as a beneficial tool for the manufacturing managers to decide whether changes in SC should be made and to show the potential increase in customer satisfaction thanks to the integration AM into the SC. Moreover, the elaborated model is planned to be implemented in the form of an information technology (IT) tool the use of which will support managerial decisions about providing changes within an SC. The authors are currently researching universal models of SC linked to the production process for a given class of enterprises, as well as the possibility of decomposing this system to model the decision-making process using Petri nets.

7. Conclusions

The proposed approach in support of decision making related to the implementation of AM in an SC is based on the use of a Petri net. In our case, a production process was considered in which one production workstation could be replaced with AM technology; for this case, a decision model was built to operate alongside mass, customized production (MC) strategy. The MC strategy aims to meet the personalization of products. For this purpose, enterprises are producing short series of personalized products. In order to be able to effectively realize this strategy, managers are looking for solutions to support decision-making about changes, e.g., in the SC. The

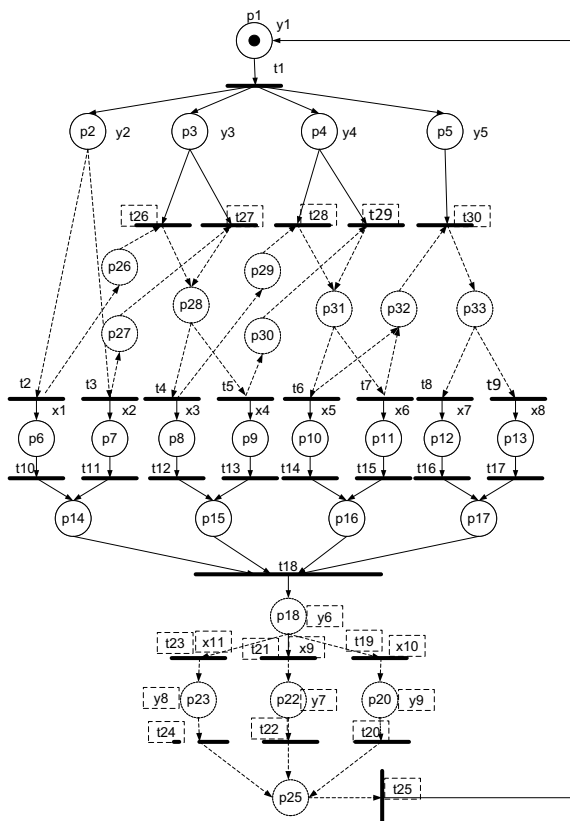


Fig. 4. Revised Petri net-based model of an AM technology-driven SC.

presented Petri net-based decision model can serve as an example of such a solution and present the potential increase in customer satisfaction thanks to the integration AM within the SC.

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