CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2022

3rd Conference on Production Systems and Logistics

Cross-Company Routing Planning: Determining Value Chains In A Dynamic Production Network Through A Decentralized Approach

Julia Markert[1], Dominik Saubke[1], Pascal Krenz[1], Lothar Hotz[2]
[1]*Helmut-Schmidt-University, Hamburg, Germany*
[2]*Hamburger Informatik Technologie-Center, Hamburg, Germany*

Abstract

Demand-based, local production will gain relevance in the context of sustainability and circular economy. One way to implement local value creation is through establishing highly dynamic networks that consolidate the competencies of regional manufacturers. Consequently, the structure of the value chains needs to be determined ad hoc dependent on demand. This is a rather challenging task due to the dynamics within such networks and the flat hierarchies. Traditionally, value chains are defined and controlled in a centralized form by a lead firm or a separate stakeholder (e.g. Intermediary, Broker). However, to accommodate the dynamics of demand and the increasing complexity of products, we propose a decentralized form of coordination. The basic idea is to upscale Routing Planning, used in Process Planning, to a network level. Meaning instead of a centralized instance within a company defining the production steps, the stakeholders will collaboratively determine the cross-company Routing Plan, effectively building the value chain. Thus, the accumulated experience and knowledge of all stakeholders can be utilized to efficiently fulfil current customer demand, since the value chain will be executed by the same stakeholders that created it. But in order to coordinate the sequencing of operations by multiple stakeholders, suitable methods need to be implemented. We look at a strategy to facilitate such a collaboration between companies and demonstrate one possible technical implementation based on AI planning using Planning Domain Definition Language (PDDL).

Keywords

Production network; Process Planning; Collaborative planning; Value chain; AI planning

1. Introduction and Motivation

While global value creation with division of labour is prevalent nowadays, in recent years the concept of producing locally in small networked sites has gained an increasing amount of attention [1–3]. There is more and more research dealing with new, demand-based local production principles, such as Urban and (Re-) Distributed Manufacturing. These concepts aim to reach the goals of a sustainable production and fulfil customers' growing desire for increasingly individualized products [4,5,1]. Larsson even went so far as to state that "there will be a need to re-shape entire value chains and a large share of the corporate landscape" [1]. Additionally, the Covid-19 pandemic has accelerated research interest in local production as an exploding need for medical equipment has shown the risky dependence on global value chains [6,2]. The local production of masks was able to alleviate the shortage, effectively demonstrating an important advantage of local production - resilience [2].

DOI: https://doi.org/10.15488/12135

One challenge of local production is being able to adapt to demands changing fast due to increasing product complexity and individualization. To achieve a high product variety and small batch sizes, a multitude of production processes has to be covered by local stakeholders. Multiple companies have to collaborate in networks in order to combine their competences and to fulfil these requirements [7]. However, constructing highly flexible, adaptable value chains in local networks calls for appropriate strategies, because unlike in mass production, long-term collaborations with carefully selected partners and high degrees of insight into suppliers' production are not feasible. Instead a high level of dynamics develops within the structures of local value creation, which in turn reduces transparency. For that reason, we will discuss a decentralized strategy for creating value chains in the described environment and one possible technical solution based on AI planning (Artificial Intelligence) as it "has been successfully applied for decades in several areas" [8].

2. Theoretical Background

This paper will talk about the idea to use principles from Operations Planning and Scheduling (OPS), more specifically Process Planning (PP), in order to create value chains in a decentralized network of local small and medium-sized enterprises (SME). Therefore, Chapter 2.1 will discuss existing concepts for the planning of value chains in networks while Chapter 2.2 will give some fundamentals regarding Process Planning.

2.1 Network Planning

The network's status as a very important and most modern organisation form of producing companies [9] is in line with the increasing trend of outsourcing, which basically means transferring tasks and processes to an outside party [10]. Over the last decades, outsourcing has become a standard practice in many companies for various reasons, such as decreasing costs and lowering the vertical range of manufacture [9,10]. Industrial production today is shaped by a high degree of often international division of labour. That means, companies producing physical goods build a network of specialized suppliers and other firms to reach their production goals. The interaction and communication along the value chain is facilitated by, e.g., product or industry standards, modularization and platform technologies. However, when parts or even just production steps are outsourced, costs and effort for coordinating production will increase [9]. Usually the focal company selling the end product will procure the needed parts itself by distributing the necessary orders to suppliers. Having a network of suppliers, with whom a company works regularly, as well as the mentioned interaction mechanisms can therefore make this process more efficient. This hierarchical concept works well when the production program is planned months or years ahead, but comes to its limits when the production needs to be dynamic with individualized, everchanging products in small batch sizes or single product orders [11,12].

This paper targets a decentralized, local production as another form of value creation next to global production with division of labour. In such a production aiming to serve local demands ad hoc, a new dynamic develops. Because the sales market in a local production is small, the batch sizes are as well, but the product variety is very high. This leads to fluctuating demands in a short time while production has to be handled by comparatively few manufacturers, since resources are limited by the regionality of local production. In order to adequately handle this dynamic in combination with the mentioned parameters (local, on demand, high product variety, fewer producers) new solutions are needed.

One of these is a concept introduced in the late 90s by Schuh et al. [7] - the Virtual Factory[1]. Several companies come together to form a larger, Virtual Factory to easier handle short term production in small batches. There is a stable and a dynamic component involved in such a Virtual Factory [7]. The relationships

---

[1] This is not to be confused with the virtual factory concept as introduced in 1993 by Onosato and Iwata [13] that focuses on modelling manufacturing. More recent information on this strain of virtual factory research can be found, e.g., by Debevec et al., who dealt with simulating production processes in SMEs [14], or Yildiz et al., who wrote about a digital twin-based virtual factory [15].

within the network should be stable, as they are in a typical production network as well, while the processing of orders is done dynamically through "activating" networks for each order [7]. Schuh et al. [7] defined six intercorporate services to manage the Virtual Factory network, one of them being the "broker". The "broker" is usually an independent party responsible for – among other tasks such as acquiring customers – distributing the competences of the companies to where they are needed while roughly defining prices [7]. The broker may also initiate the so called "active networks", meaning essentially the value chains that will go into action for a specific order or project [7].

2.2 Operations Planning and Scheduling and Process Planning

Operations Planning and Scheduling (OPS) essentially describes all the organisational functions that need to be fulfilled to bring a product design into production and to the customer [16,17]. Process Planning (PP) is one part of OPS, the other part is Production Control (also referred to as Production Planning and Control or PPC). PP encompasses the planning necessary to ensure the economically sound manufacturing in line with production requirements and it is typically done once without reference to a specific order [18,19]. As shown in Figure 1, the tasks of PP can be divided into three categories, short-, medium- and long-term as introduced by Eversheim [19] and referenced by, e.g., Bauernhansl and Spur [18,20]. PPC on the other hand includes the measures needed to fulfil actual orders based on the results of PP [17].

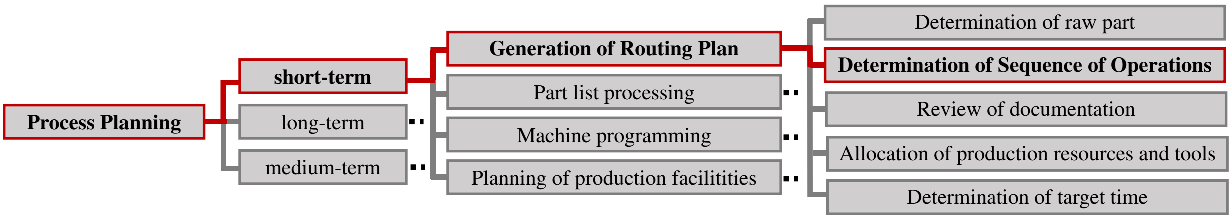


Figure 1: The structure of Process Planning (with selected details) [18,19]

One result of PP is the Routing Plan (RP), which is described as "a plan defining the sequence of operations to be performed in order to produce a part or an assembly, i.e. the product's path through the production process" [16]. Besides the production steps in the right order, a RP will include information regarding the type of raw part to start with, production resources and tools as well as the target time for each step [19]. For this paper, the focus will be RP, especially the sequence of operations, marked by red borders in Figure 1.

3. Concept: Implementing Operations Planning and Scheduling on a Network Level

Modern local production leads to a necessity to manufacture dynamically and on-demand to be able to fulfil customer needs in times of individualization without having large amounts of products in warehouses available to do so. The dynamic nature of networked production also requires a cross-company organisation that will be able to keep up the fast pace of small-batch and single product orders. Since building value chains spanning multiple companies bears many similarities to building an in-house RP (refer to Chapter 2.2), it can be useful to apply the methods and tasks of RP to a network/cross-company level. The extensive knowledge and research on OPS and specifically RP already available can then be used as a baseline for adapting existing concepts and deriving new ones for the given context.

3.1 Approach for the decentralized determination of value chains

In a hierarchical network (as introduced in Chapter 2.1) the lead firm typically uses its network of suppliers to coordinate value creation by acquiring materials and parts as well as outsourcing production. Two examples for this kind of centralized approach are Wintelism, which is described as the "extensive outsourcing of component production to enable industrial structures to become less vertically and more horizontally integrated" [21], and Sturgeon's modular production networks [22]. In addition, the planning departments of each company involved in the network generate in-house RPs, meaning they determine the sequence of operations within their own company and allocate the production resources (Figure 1) [19].

In centralized networks it is the lead firm's task to configurate the cross-company value chains. There are usually relatively stable planning horizons that facilitate mid- to long-term planning. However, when dealing with dynamic, heterarchical and decentralized networks there are no steady planning periods. As a result, the generation of value chains needs to happen faster and adapt dynamically, so that even single product orders can lead to entirely new value chains. In order to move away from the more permanent structures of value chains, the network can be viewed as one virtual company, similar to Schuh's Virtual Factory [7] (refer to Chapter 2.1), with the SMEs representing production resources. This also serves the depiction of the heterarchical structure of a decentralized network. Using this analogy, value chains correspond to the RPs introduced in Chapter 2.2 with the difference that they now function as cross-company RPs (ccRP). This view and the introduction of ccRPs should allow for better reactivity in local, decentralized networks.

However, other than in the creation of traditional RPs, there is no superior central entity that knows all the details of the production of all the companies involved in the network. That is because there is often a lot of experience involved in writing RPs. This is categorized as tacit knowledge, i.e., it is not formalized and thus difficult to share [23]. Nonaka calls the process of making tacit knowledge sharable by turning it into explicit knowledge "externalization" [23]. Externalizing the knowledge needed for common routing planning from individuals of the companies in order to create such a central entity would be time-consuming and expensive, given that the involved companies would even agree to share their knowledge to the required extent. The aforementioned dynamics of processes and structures further add to the difficulties of externalization. As a result, when working with a heterarchical, dynamic network, it is highly unlikely that a central entity has the knowledge needed to determine the best possible ccRPs for all involved companies or even any at all.

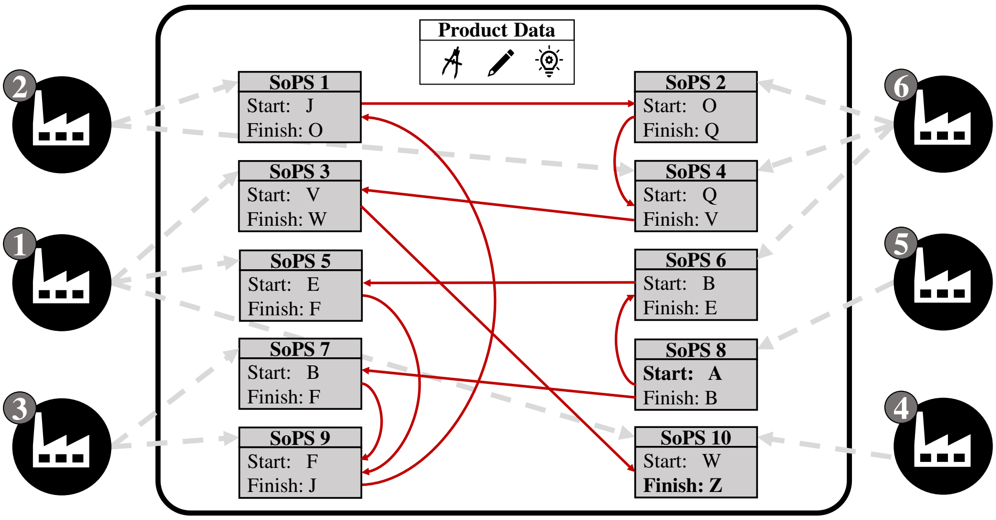
We therefore suggest to avoid the externalization process altogether by **taking a decentralized approach to ccRP**. That means instead of gathering knowledge from the companies, that knowledge stays where it is, but is still used to create the ccRPs. According to Krenz, the complexity of the knowledge that is to be shared needs to be reduced, so that the stakeholders of the network are able to collaborate [12]. In summary, the concept idea we propose in this paper seeks to create value chains in a decentralized way through leaning on the principles of OPS and PP and upscaling them to a network or cross-company level.

This is also an important point of differentiation from Schuh et al.'s concept of a Virtual Factory, as described in Chapter 2.1. While it also involves a decentralized, local network, Schuh et al. still assign various functions or centralized roles to distinct stakeholders of the network such as the "broker", while the ccRP concept relies on decentralized collaboration of the companies within the network instead.

3.2 Introduction of a possible strategy

In order to implement decentralized ccRP in dynamic networks, it is necessary to find a way for process planners from all the network companies to contribute to a cumulative plan in a simple and fast manner. The simplest form of collaboration would be **experts discussing and developing a plan together**. This however bears several issues such as the group size getting too large for useful discussions, experts being invited unnecessarily and the need for a skilled and neutral facilitator. Overall this approach would incur unreasonably high costs and consume a lot of time compared to the central approach while having presumably little advantages. In conclusion, the decentralized approach needs to allow planners to be able to work independently from one another, ideally in regards to time and location, also called **asynchronous communication** [24], and it needs to be well structured and efficient. This is typically prevalent in cross-company collaborations [25].

For ccRP the goal is to sequence the economically best value chains while using the planners' expertise without the need for direct communication between companies. For this strategy proposal we, on the one hand, drew inspiration from **collaboration in communities**, where everyone may contribute their expertise. But on the other hand, since ccRPs are a planning problem, we also relied on research on automated planning and scheduling (AI planning), namely **using world states for computing plans instead of defining processes** [26]. The focus is to develop an approach **in which process planners can work together without directly communicating**. Instead they contribute their knowledge and competence in such a form, that an intelligent and autonomous planning system (example in Chapter 3.3) can generate an optimized ccRP and thus create a cohesive value chain. That strategy is visualized in Figure 2. The premise is a dynamic, heterarchical network, where product development can be done by a company, an engineer without own production capacities or a community of designers, etc. There is no central entity distributing/outsourcing production steps. Instead, the Product Data is provided to a network of process planners that will then derive the production steps their own company can do and enter them into a network system. However, they do not actually describe what they are doing in production or how they are doing it. Instead the only thing entered into the system is how the product changes, i.e., the planners describe the product state they can start production with and the product state at the end of their company's part in the production process, e.g. bar stock - gear shaft (unhardened). They therefore contribute a **Sequence of Product States (SoPS)**.



SoPS = Sequence of Product States

Figure 2: Decentralized, cross-company Routing Planning and value chain creation

In Figure 2 those product state descriptions are represented by letters, i.e., the starting state of SoPS 1 is "J" and the finishing state is "O". These descriptions are used to find interfaces between the companies, e.g., between SoPS 1 ("O" as the finishing state) and SoPS 2 ("O" as the starting state). The possibility of branching production sequences, i.e., sequences that can be processed in parallel until the parts are joined together, e.g., in assembly, is not visualized in Figure 2 for reasons of clarity and comprehensibility. In such a case, the start or end state would be the combination of two states, e.g., "C and D". The necessary formalization of the state descriptions is discussed in Chapter 4. According to Dietl, companies will delimit their value creation activities in such a way that as little implicit knowledge as possible needs to be transferred in between steps [27]. In other words, the steps of value creation are separated in a way that the knowledge exchange at the interfaces is reduced to a minimum transfer of external knowledge [27]. The stakeholders integrate their implicit knowledge into the product and thus transfer it by changing the product state [27,12]. When all steps are entered, several viable paths are calculated (for reasons of clarity and comprehensibility only two are shown here) and one or more optimized paths (depending on the system) are determined. Those are the ccRPs available for PPS (refer to Chapter 2.2), i.e., the implementation of the value chains. When feeding the system with further information such as capacity, price, transport distances and number of involved companies, the most fitting ccRP at a given time can be chosen according to selected criteria. This is however a separate topic and not further discussed in this paper. Overall, the presented strategy would allow the ccRPs to develop in a self-organizing process in which the network companies choose the interfaces. Therefore, this strategy for configurating value chains can be considered heterarchical.

This may lead to considerable benefits in terms of network dynamics and reactivity. There are several viable options for a value chain available, so one alternative can be chosen to be used for actual production. Additionally, the chosen path can easily be changed mid-production in case of unforeseen events since alternatives have already been determined beforehand. When several companies are capable of performing the same steps, it creates redundancy and therefore resilience. This enables the network to adapt in case, e.g., capacity issues occur and one company is not able to deliver. The strategy also has the advantage that the process planners can work entirely independent of one another, they do not have to spend time to understand each other's work or to standardize plans cross-company. They can use their expertise without sharing it, which is especially important when sensitive, inside knowledge of companies is involved. Information necessary for planning is fed to the system to be processed instead of being shared in the network community.

3.3 Technological approach for the implementation of decentralized ccRP

3.3.1 AI Planning using the Planning Domain Definition Language (PDDL)

The presented strategy for decentralized planning illustrates that this problem can be solved with the methods and systematics of general decentralized planning principles. Decentralized networks of production units already require a high planning effort with a small number of stakeholders and less complex products, such systems exhibit multitude branching, which can only be evaluated with computer support [28].

The so-called research area of AI Planning within the technology field of AI deals with the solving of complex planning tasks with high numbers of possible solutions. Solving these problems involves the change of states through sets of *action*s. The initial situation is a problem with an initial state and a final state, the *goal*. Hereby details of the change or effect are not considered, i.e., actions are only described through input (a *precondition*) and output (an *effect*) states. In our use case, this leads to a special advantage, since company-internal knowledge of concrete production steps is not revealed in detail. [26,29]

The implementation technology pursued here is PDDL. With the introduction of PDDL in 1998, inspired by the STRIPS (Stanford Research Institute Problem Solver) formalism, a standardization of AI planning languages was developed [30,31]. PDDL is considered to currently be one of the most common solutions to implement AI planning [30] and thus suitable to address the underlying planning problem of ccRP. The solution to a planning problem, the fulfilment of target conditions, is considered to be a concatenation of actions, i.e., a concatenation of Sequences of Product States (SoPS) as shown in Figure 2 (Chapter 3.2). Those SoPS are entered into the system by the individual stakeholders in the production network. As already described, they can contain different numbers of production and process steps. Each SoPS contains a change of the state. Furthermore, following the principle of PDDL, each SoPS will be modelled as an action and will be assigned a precondition and an effect. By matching this information, the SoPS are aligned to find a path to the end-state (*goal*). In the next section a PDDL implementation approach is presented. [26,28,32]

3.3.2 Approach for the implementation of PDDL in the given context

As an example, in Figure 3, we provide a PDDL model for the SoPSs depicted in Figure 2 as a domain model and a problem model, respectively. The domain model describes the rules of RP as predicates and actions, while the problem model describes the actual task at hand, e.g., to compute the plan from subproduct "A" to subproduct "Z". Another task would be to compute the plan from subproduct "B" to subproduct "F". The intermediate production results of each SoPS are named SUBPRODUCTS and modelled as objects. One action (named SoPSx, where x is the numbering of the SoPS in Figure 2) models one SoPS with a certain SUBPRODUCT as precondition ("Start") or effect ("Finish"). Furthermore, a specific SUBPRODUCT is marked as initial state (i.e., "A") and another as goal (i.e., "Z").

```
(1) Problem Model in PDDL

Objects:
Subproducts: A, B, E, F, J, O, Q, V, W, Z
In PDDL:
(:objects A, B, E, F, J, O, Q, V, W, Z)

Initial State:
SUBPRODUCT(A) is true, i.e.,
A is the start of the process

In PDDL:
(:init (SUBPRODUCT A))

GOAL specification:
SUBPRODUCT(Z) is true, i.e., Z shall be produced

In PDDL:
(:goal (SUBPRODUCT Z))
```

```
(2) Domain Model in PDDL

Predicates:
SUBPRODUCT(x) – true iff x is a subproduct
In PDDL:
(:predicates (SUBPRODUCT ?X))
; whereby ?X represents a variable

Action:
Description: Each SoPS of Figure 3.2
is represented by one action.

Precondition is the „Start‟ subproduct
Effect is the „Finish‟ subproduct

In PDDL:
(:action SoPS1                        (:action SoPS6
   :precondition (SUBPRODUCT J)          :precondition (SUBPRODUCT B)
   :effect (SUBPRODUCT O))               :effect (SUBPRODUCT E))
(:action SoPS2                        (:action SoPS7
   :precondition (SUBPRODUCT O)          :precondition (SUBPRODUCT B)
   :effect (SUBPRODUCT Q))               :effect (SUBPRODUCT F))
(:action SoPS3                        (:action SoPS8
   :precondition (SUBPRODUCT V)          :precondition (SUBPRODUCT A)
   :effect (SUBPRODUCT W))               :effect (SUBPRODUCT B))
(:action SoPS4                        (:action SoPS9
   :precondition (SUBPRODUCT Q)          :precondition (SUBPRODUCT F)
   :effect (SUBPRODUCT V))               :effect (SUBPRODUCT J))
(:action SoPS5                        (:action SoPS10
   :precondition (SUBPRODUCT E)          :precondition (SUBPRODUCT W)
   :effect (SUBPRODUCT F))               :effect (SUBPRODUCT Z))
```

Figure 3: (1) Problem description that has a specific start and goal; (2) Domain model describing the SoPS as actions

Given this domain and problem model to PDDL, it will compute a plan (or multiple plans) that takes the action definition into account, i.e., it would compute a value chain. According to the dependencies, two paths are possible in our example, one from SoPS8 via SoPS7 to SoPS9 and one via SoPS6 and SoPS5 (Figure 4). In case of branching production sequences (as mentioned in Chapter 3.2) the precondition of an action would consist of two or more subproducts, e.g., `(:action SoPSWithAssembly :precondition (and (SUBPRODUCT W1) (SUBPRODUCT W2)) :effect (SUBPRODUCT AssembledZ))`.

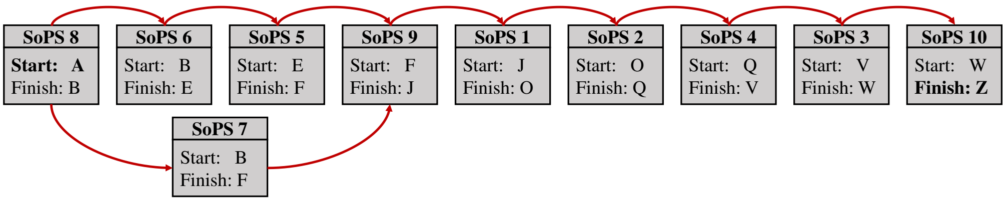


Figure 4: Possible paths in the given example according to their dependencies

3.3.3 Assembling ccRPs using Heuristic Methods

The core of PDDL is to use a heuristic search algorithm [33] for computing appropriate plans as described, i.e., PDDL implements such an algorithm, e.g., A*. Alternatives to PDDL, which use heuristic search, are distributed AI algorithms based on agents (agent-based algorithms), where each SoPS would be considered as one agent and by following a negotiation process the agents would compute a plan. Other alternatives would be evolutionary algorithms (EA) which would compute plans through creating plans by mutating them randomly and evaluating those through domain related criteria such as order of SoPS (selection).

4. Critical Analysis of the Proposed Concept

When analysing the presented concept concerning its feasibility in a real application, the criteria must be of **strategic**, **operational** or **technical** nature. In terms of strategic application, the concept of a decentralized collaborative OPS seems particularly suited to the requirements of new production structures, with increasingly blurred physical boundaries between companies.

In operational terms, it is to be mentioned that the strategy presented in Chapter 3.2 is still in the early stages and only an outline. There are several issues to be detailed and addressed in future research to develop the strategy into an implementable concept, since at this point it only describes a way to get to the description of technically feasible value chains. Before one of those can be chosen for implementation, they need to be evaluated using criteria like timing and cost. It is also thinkable to include other variables for choosing one of the plans, such as energy efficiency of production, transport distances, etc. Additionally, the "perfect" value chain may still not be implementable at any given time due to capacity and scheduling issues. RP is only one step in the interface between design and production, our strategy needs to be embedded in a holistic concept covering all of OPS in order to work. Other issues to be considered in future research are, e.g., data storage and security, but also issues of motivation, incentives to participate, building trust in a network, etc.

When critically examining the technical implementation, the main focus is on the description and formalization of the SoPS, especially since the system needs to recognize when two planners are describing the same state in different words. Precondition, parameter and effect must use a uniform language in order to be linked with each other. An approach to formalization could be the use of Natural Language Processing (NLP). This is a solution for a further improved human-computer interaction and a common tool in the field of AI. In addition, an investigation and more exact statement in regards to the critical size of the network seems meaningful, especially for concrete decisions in technology selection (PDDL Toolboxes, Heuristic Search Algorithm, etc.). In general, the topic of quality management in such a system is likely to face new challenges, which are already evident here at the beginning when evaluating planning solutions. Also, when selecting and applying different methods from the field of heuristic search, attention must be paid to their result orientation. Depending on the modelled optimization criteria, the heuristic search will provide optimized solutions. In our example we focused on dependencies between the SoPS. Other criteria could include the ones mentioned above on the operational level. Thus, when considering value chains, the chosen termination criterion will have a direct impact on quality, cost, sustainability and customer satisfaction.

5. Outlook

In conclusion, using decentralized, cross-company Routing Planning in order to dynamically create value chains for local networks while relying on existing knowledge within the involved companies seems to be a promising approach. For one it draws on decades of research on Operations Planning and Scheduling as well as the often extensive expertise of experienced process planners, but it also combines these with state-of-the-art information technologies from the fields of AI planning and Heuristics. In our approach the knowledge stays with the experts, but is still utilised and arranged by an intelligent system in order to generate flexible value chains in a decentralized way.

This opens up several possibilities for future research. Firstly, on an operational level, as mentioned in the critical analysis, the strategy of using changes in the product state described by a network of process planners to find a Routing Plan should be developed further and with more detail. Following that, the second part of Operations Planning and Scheduling, Production Control (also known as Production Planning and Control), could be addressed. In this paper we looked at using Process Planning on a cross-company level and decentralizing it. The next logical step would be to explore whether or not Production Control principles are also applicable and beneficial to be used in networked production.

Furthermore, the technological approach discussed in Chapter 3.3 will be optimized through an ongoing project to implement a decentralized, local production network in the Greater Hamburg area. Going into more detail and possibly simulating a test run will be a next step. It would also be expedient to address the issue of comparing and assessing the cross-company Routing Plans created by the heuristic based on selected criteria. Additionally, using PDDL and heuristic methods is just one possible way to go. It might be interesting to explore other technologies that could be suitable for the presented problem.

Acknowledgements

This research is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr [project: Production Next Door].

References

[1] Larsson, M., 2018. *Circular business models: Developing a sustainable future*. Palgrave Macmillan, Cham.

[2] Peters, A., Guitart, C., Pittet, D., 2021. Addressing the global challenge of access to supplies during COVID-19, in: Hadi Dehghani, M. (Ed.), *Environmental and Health Management of Novel Coronavirus Disease (COVID-19).* Elsevier Science & Technology, San Diego, pp. 419–441.

[3] Spath, Dieter (Hrsg.), Ganschar, O., Gerlach, S., Hämmerle, M., Krause, T., Schlund, S., 2013. *Produktionsarbeit der Zukunft - Industrie 4.0: Studie*. Fraunhofer Verlag, Stuttgart, 150 pp.

[4] Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. *Journal of Cleaner Production 106*, 654–668.

[5] Krenz, P., Stoltenberg, L., Markert, J., Saubke, D., Redlich, T., 2022. The Phenomenon of Local Manufacturing: An Attempt at a Differentiation of Distributed, Re-distributed and Urban Manufacturing, in: Andersen, A.-L. et al. (Eds.), Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems. *Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2021) and the 10th World Mass Customization & Personalization Conference (MCPC2021)*, 1st ed. 2022 ed. Springer International Publishing; Imprint Springer, Cham, pp. 1014–1022.

[6] Hartig, S., Duda, S., Hildebrandt, L., 2020. Urgent need hybrid production - what COVID-19 can teach us about dislocated production through 3d-printing and the maker scene. *3D printing in medicine* 6 (1), 37.

[7] Schuh, G., Millarg, K., Göransson, Å., 1998. *Virtuelle Fabrik: Neue Marktchancen durch dynamische Netzwerke*. Hanser, München, 186 pp.

[8] Vallati, M., Kitchin, D., 2020. *Knowledge Engineering Tools and Techniques for AI Planning*, 1st ed. 2020 ed. Springer International Publishing; Imprint Springer, Cham, 277 pp.

[9] Schuh, G., 2006. *Produktionsplanung und -steuerung: Grundlagen, Gestaltung und Konzepte*, 3., völlig neu bearb. Aufl. ed. Springer, Berlin, Heidelberg, 876 pp.

[10] van Weele, A.J., Eßig, M., 2017. *Strategische Beschaffung: Grundlagen, Planung und Umsetzung eines integrierten Supply Management*. Springer Gabler, Wiesbaden, 631 pp.

[11] Buxbaum-Conradi, S., 2018. *Global and local knowledge dynamics in an industry during modular transition: A case study of the Airbus production network and the Aerospace Cluster in HH*, Northern Germany. Diss., HH.

[12] Krenz, P., 2020. *Formen der Wissensarbeit in einer vernetzten Wertschöpfung*. Diss., Hamburg.

[13] Onosato, M., Iwata, K., 1993. Development of a Virtual Manufacturing System by Integrating Product Models and Factory Models. *CIRP Annals 42 (1)*, 475–478.

[14] Debevec, M., Simic, M., Jovanovic, V., Herakovic, N., 2020. Virtual factory as a useful tool for improving production processes. *Journal of Manufacturing Systems 57*, 379–389.

[15] Yildiz, E., Møller, C., Bilberg, A., 2020. Virtual Factory: Digital Twin Based Integrated Factory Simulations. *Procedia CIRP 93*, 216–221.

[16] CIRP - The International Institution for Production, 2020. *Dictionary of Production Engineering III – Manufacturing Systems Wörterbuch der Fertigungstechnik III – Produktionssysteme Dizionario di Ingegneria della Produzione III – Sistemi di produzione*. Springer Vieweg, Berlin, Heidelberg.

[17] Minolla, W., 1975. *Rationalisieren in der Arbeitsplanung: Schwerpunkt Organisation*. Diss.

[18] Bauernhansl, T. (Ed.), 2020. *Fabrikbetriebslehre 1: Management in der Produktion*, 1. Aufl. 2020 ed. Springer Vieweg, Berlin, Heidelberg, 388 pp.

[19] Eversheim, W., 1989. *Organisation in der Produktionstechnik: Arbeitsvorbereitung*, Zweite, neubearbeitete Auflage ed. Springer Berlin Heidelberg; Imprint; Springer, Berlin, Heidelberg.

[20] Spur, G., Stöferle, T., 1994. *Fabrikbetrieb*. Hanser, München, 385 pp.

[21] Hart, J.A., Kim, S., 2002. Explaining the Resurgence of U.S. Competitiveness: The Rise of Wintelism. *The Information Society 18 (1)*, 1–12.

[22] Sturgeon, T.J., 2002. Modular production networks: a new American model of industrial organization. *Industrial and Corporate Change 11 (3)*, 451–496.

[23] Nonaka, I., 1994. A Dynamic Theory of Organizational Knowledge Creation. *Organization Science 5 (1)*, 14–37.

[24] Li, W.D., Qiu, Z.M., 2006. State-of-the-art technologies and methodologies for collaborative product development systems. *International Journal of Production Research 44 (13)*, 2525–2559.

[25] Jiang, P., Shao, X., Qiu, H., Li, P., 2008. Interoperability of Cross-organizational Workflows based on Process-view for Collaborative Product Development. *Concurrent Engineering 16 (1)*, 73–87.

[26] LaValle, S.M., 2006. Planning Algorithms. Cambridge University Press, Cambridge.

[27] Dietl, H., 1993. *Institutionen und Zeit*. Zugl.: München, Univ., Diss., 1991. Mohr, Tübingen, 246 pp.

[28] Nägele, L., Schierl, A., Hoffmann, A., Reif, W., 2018. Automatic Planning of Manufacturing Processes using Spatial Construction Plan Analysis and Extensible Heuristic Search. *Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2018) - Volume 2*, pages 576-583.

[29] Russell, S.J., Norvig, P., 2016. *Artificial intelligence: A modern approach*, Third edition, Global edition ed. Pearson, Boston, Columbus, Indianapolis, 1132 pp.

[30] Haslum, P., Lipovetzky, N., Magazzeni, D., Muise, C., 2019. *An introduction to the Planning Domain Definition Language*. Morgan & Claypool, San Rafael, California, 169 pp.

[31] Wodecki, A., 2019. *Artificial Intelligence in Value Creation*. Springer International Publishing, Cham.

[32] Tencent Research Institute, Internet Law Research Center (CAICT), Tencent AI Lab, Tencent open platform, 2021. *Artificial Intelligence*. Springer Singapore, Singapore.

[33] Edelkamp, S., 2012. *Heuristic search: Theory and applications*. Morgan Kaufmann, Waltham, MA, 836 pp.

Biography

Julia Markert, M.Sc. (*1996) has been a research assistant at the Institute of Production Engineering (LaFT) within the Department of Mechanical Engineering of Helmut-Schmidt-University in Hamburg since 2021. She has a background in Production Engineering and her current research focus is on the creation and coordination of dynamic value chains in local production networks.

Dominik Saubke, M.Sc. (*1989) has been a research assistant at the Institute of Production Engineering (LaFT) within the Department of Mechanical Engineering of Helmut-Schmidt-University in Hamburg since 2021. With several years of practice experience in Product Engineering and Product Development his current research focus is production-readiness in collaborative crowd design processes.

Pascal Krenz, Dr.-Ing. (*1983) has been a research assistant at the Institute of Production Engineering (LaFT) within the Department of Mechanical Engineering of Helmut-Schmidt-University in Hamburg since 2011. He leads the research area on local production at the Institute and related research projects.

Lothar Hotz, Dr. rer. nat. (*1960) is CEO and project leader at the Hamburger Informatik Technology-Center e.V. (HITeC) and the University of Hamburg. He researches mainly for topics in the field of Artificial Intelligence (i.e., machine learning, knowledge-based systems, constraints, planning, configuration systems, computer vision) and semantic-based Open Data portals.