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A literature review and cluster analysis of the Aachen production planning and control model under Industry 4.0

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Abstract

Industry 4.0 technologies influence how production is planned, scheduled, and controlled. In literature, different classifications of the tasks and functions of production planning and control (PPC) exist, of which one is the German Aachen PPC model. This paper conducts an exploratory literature review by reviewing 48 publications on a full-text basis. Based on the review, a cyber-physical PPC architecture is proposed, which incorporates current Industry 4.0 technologies, current optimisation methods, optimisation objectives, and disturbances, relevant for the realisation of a PPC system in a smart factory. A classification scheme is developed as a basis for two cluster analyses that reveal researched and unexplored tasks and functions of the Aachen PPC model. Current approaches focus on the in-house PPC, particularly on the control using real-time information from the shop floor. Future research directions are proposed for the unexplored tasks and functions of the Aachen PPC model.

Keywords: Production planning and control; Industry 4.0; Industrial Internet of Things; Exploratory literature review

1. Introduction

The main task of production planning and control (PPC) is to plan and schedule the production and ensure its realisation by dealing with different disturbances occurring during the execution [1]. A PPC concept consists of four objectives that are also relevant in the context of Industry 4.0 [2]: high capacity utilisation, short lead times, high schedule reliability, and low inventory level [3]. Therefore, the management has to implement a strategy of

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standardisation, integration, decentralisation, and centralisation [4]. The technological progress in computer science, information and communication technologies, and manufacturing automation summarised as the cyber-physical production system (CPPS) [6] influences the interaction between PPC functions and the resources needed for the production. This technological change is referred to in the literature as Industry 4.0 and Industrial Internet of Things [7, 8]. The term Industry 4.0 was mentioned the first time on a fair in Hannover, Germany, described as a new industrial revolution, driven by the Internet of Things consisting of interconnected cyber-physical systems [9]. Following the reasoning of [7], that the terms Industry 4.0 and Industrial Internet of Things merely differ concerning the stakeholders, representation, and geographical focus [10], this paper uses both terms as synonyms.

A categorisation of PPC's existing concepts in the German literature carried out in [11] revealed a diverse terminology and classification of the steps and processes of PPC. Because the Aachen PPC model published in [5] is a widespread concept in the German-speaking countries [11], it serves as a basis for the present literature review. The Aachen PPC model describes PPC from four different views. The task view specifies the tasks of PPC in a universal and hierarchical abstraction. The process view provides a temporal and logical order for these tasks giving a procedure for order fulfilment. The process architecture view differentiates between network and enterprise-level tasks and processes while establishing a connection between the task and process view. The function view describes the requirements to an IT-system that supports PPC, and each function belongs to one of the tasks of the task view [5]. To investigate which approaches recent literature suggests for solving the tasks of the Aachen PPC model using IT-systems, the task and function view are used to classify and structure the findings in this paper.

This literature review aims to give an overview of current advances in PPC in Industry 4.0. Three sub-goals are defined:

1. Identification of current Industry 4.0 approaches for planning and control of production processes,
2. Classification of novel approaches according to the functions of the Aachen PPC model,
3. To reveal researched and unexplored tasks and functions of the Aachen PPC model of Industry 4.0.

The focus is aligned to the manufacturing industry, in particular to the PPC of products and services. Approaches primarily considering environmental aspects and sustainability are not subject to this literature review. The literature review does not raise a claim to completeness.

Chapter 2 gives an overview of the related work about outlooks on future research and development challenges of PPC in the context of Industry 4.0. Chapter 3 describes the methodology and results of the exploratory literature review. A cyber-physical PPC architecture and the results from two distinct cluster analyses based on a developed classification scheme are presented. Chapter 4 discusses researched and unexplored fields and future research perspectives for PPC in Industry 4.0 concerning the related work of chapter 2. Chapter 5 summarises the findings and closes the paper with an outlook for future work.

2. Related work

[2] examine the tasks of the Aachen PPC model, particularly the planning aspect in the context of Industry 4.0. The production requirements planning and in-house production planning will benefit from frequent delay-free data exchange between the planning system and the cyber-physical systems. That results in high quality and actuality of production data and avoids possible disturbances. The high flexibility of resources caused by Industry 4.0 will facilitate the matching of capacity offer and demand. Production requirements planning will be able to react in real-time to disturbances (machine breakdowns, capacity absence) as well as to check and adapt master and planning data frequently. The in-house production planning system can plan lot-sizes, makespan, and work-in-progress dynamically. Thereby, cross-company tasks and long-term planning tasks are still executed by centralised planning systems.

A technology-oriented view of development in PPC in the context of Industry 4.0 gives [6]. The author describes the expectations, as well as directions for research and development for CPPSs. Robustness, self-X technologies, real-time control, autonomy, and transparency, to name a few, are outlined as the main expectations. These developments are based on artificial intelligence, biological inspiration, reconfigurability, digitalisation, and the manufacturing system as a set of autonomous, cooperating holons. [6] identifies the realisation of autonomous and cooperative production systems that adapt to the context in which they operate as primary research and development challenges for CPPSs. Other research directions are the predictability and robustness of dynamic systems and the fusion of virtual systems with real systems and humans. Operating in a smart factory significantly influences the organisation of the sequential and timely order of operations and the assignment of resources.

[12] review recent research on the job shop problem in Industry 4.0. They classify the approaches into five categories: primary type, multi-machine type, multi-resource type, multi-plant type, and smart factory type. The authors also refer to the last category as the Smart Factory Flexible Job Shop Problem (SFFJSP). Based on the categories, the authors present existing concepts (e. g. exact methods and approximate methods) and novel approaches. They conclude that current research focuses on the first two categories of the job shop problem, although they do not reflect the complexity of reality. Furthermore, [12] point out the limitations and research challenges of existing approaches to solve the SFFJSP. Thereby, they will have a focus on smart decentralised scheduling utilising the smart agent and Industry 4.0 technologies like barcodes, RFID technology, and sensors, to reduce the computational workload required to solve the complex, dynamic and flexible job shop problems.

Existing scheduling techniques for the complex job shop scheduling problem in the semiconductor industry from an Industry 4.0 perspective are reviewed in [13]. They provide an overview of dispatching heuristics, hyper-heuristics and machine learning (ML), mathematical programming, and other approaches such as the shifting bottleneck heuristic, genetic algorithms, and intelligent multi-agent systems (MAS). They remark the need for decentralisation and autonomous decision making. Local decision-making is supported by a complexity reduction of the high quantity of available data through ML. The decomposition of scheduling problems is seen as beneficial to find the global optimum. Flexibility and adaptability project into areas such as rescheduling, process qualification management, lot-sizing, product portfolios, and robustness. They expect the vertical and horizontal integration of IT-systems to emerge and to integrate the supply chain, material handling systems, cluster tools, and statistical process control. They anticipate that human activities evolve from repetitive to creative tasks in a complex environment. They close with ML and MASs as promising approaches to address the different research areas and recommend a combination of the existing approaches for practice.

In distributed control architectures like MAS or holonic production systems, the control behaviour may become myopic. [14] propose a framework for PPC and Industry 4.0, establishing three categories serving as a design space for production systems that implement a distributed control architecture. Each of the categories of design, scheduling, and control, provides a set of dimensions for designing the production. The authors argue that decentralisation helps to reduce the complexity of a production system. However, at a certain degree of decentralisation, the emergent behaviour of the system becomes myopic. Myopic means the inability of the entities of a production system to anticipate the system and future consequences of their decisions. The proposed framework supports the classification of novel approaches for distributed production control.

3. Exploratory literature review

3.1. Methodology

The literature review was conducted from November 23rd, until December 28th, 2019, in German and English. It includes all journal articles and conference papers in the publication status accepted or higher in the years 2014 until 2019 since Google Trends indicates that the search popularity of "Industry 4.0" and "Industrial Internet of Things" begins to rise significantly in 2014 [15, 16]. The literature review is conducted in an exploratory manner, which means that a first search iteration with only two databases and a limited amount of publications serves for piloting and finding out the optimal search term combination and content to be stored from each publication. Based on these results, the second search iteration is carried out in an optimised manner with the remaining databases. Fig. 1 shows the paper selection process of the first and second search iteration and the corresponding databases used.

For the review of international publications, the databases Google Scholar (GoSc), ISI Web of Knowledge (WoK), and IEEE Xplore Digital Library (IEEE) were used. The databases Bielefeld Academic Search Engine (BASE), GoSc, and WISO, were utilised to identify publications from German institutions and researchers. The search in all databases was sorted by relevance and filtered by the period determined above. In GoSc, the limit *Only German search results* was not applied. Since the focus of the term "Industry 4.0" is on the German-speaking region, the term "Industrial Internet of Things" has a global focus [10]. Therefore, both terms are taken as synonyms in the literature review. By including the search term PPC, publications are selected that have an industrial reference. Due to the content of "Internet of Things", it is not necessary to explicitly include the term "industrial" in the literature search. However, it is advisable to include the term "Manufacturing execution systems", since corresponding IT-systems greatly influence the quality of PPC [4].

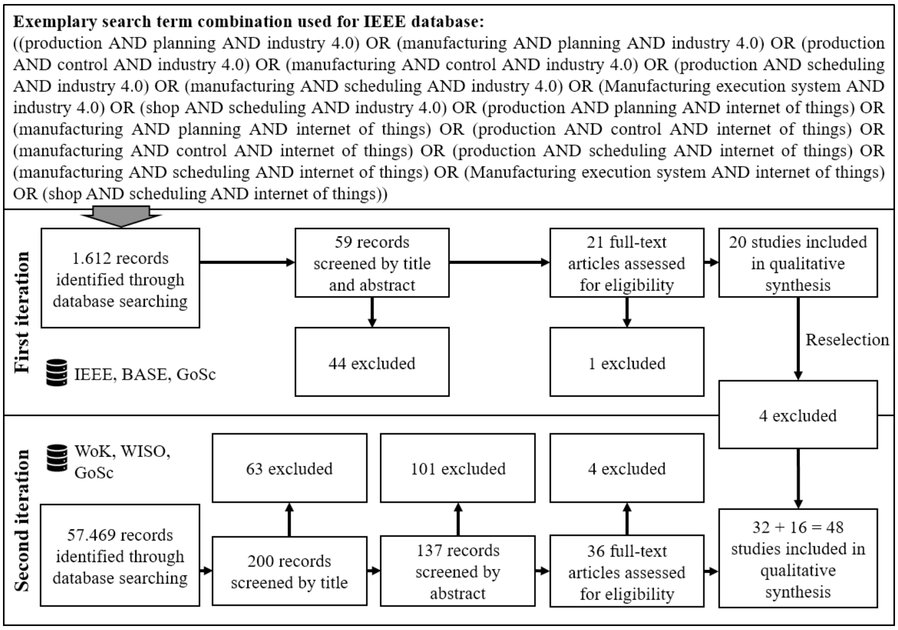

Fig. 1. Exemplary search term combination and paper selection process.

The search term combination used in IEEE consists of "production"/"manufacturing"/"shop", "planning"/"control"/"scheduling" and "Industry 4.0"/"Internet of Things", as well as "Manufacturing execution system" and "Industry 4.0"/"Internet of Things". Fig. 1 illustrates an example of the IEEE search term combination. The combination of the German terms for BASE consisted of "Produktion"/"Fertigung" and "Planung" and "Industrie 4.0" or "Produktion"/"Fertigung" and "Steuerung" and "Industrie 4.0" as well as "Manufacturing Execution System" and "Industrie 4.0".

The first search pass in the IEEE and BASE databases ascertained 1,516 (IEEE), and 96 (BASE) publications. Afterwards, the title and abstract of each publication were screened. A publication had to contribute to at least one of the three sub-goals stated in chapter 1 and had to be assignable to the considered functions and tasks from the Aachen PPC model that are shown in Fig. 2. A detailed description of each task and its respective functions is given in [4] and [5]. The screening was processed iteratively for each database until ten appropriate publications were identified. Subsequently, the full text of the selected publications was assessed for eligibility.

Since the BASE literature research identified less than ten publications, the initial search term combination was extended. The term "Industrie 4.0" was replaced with "cyber-physisch" due to the close relationship between both terms [17]. However, the modified search term combination leads only to one further publication so that the remaining five publications were collected from GoSc.

The full-text analysis was performed using the same criteria as the previous title and abstract screening. If a publication was excluded from the study due to its content in this stage, further publications were analysed. This process was executed iteratively until ten publications per database have been selected. Since the English search term combination provided many results, the term "cyber-physical" was not considered. The review of 20 publications on a full-text basis that were obtained in the first search iteration, gave confidence, that the right search term combinations were chosen. Thus, the same search term combinations were used in the second search iteration. However, the manner in which the content was stored from each publication has been adapted. The content of each publication was stored by writing down the following aspects:

- Aims and objectives (e. g. maximisation of productivity in a flow shop),
- Resources within a production environment (machines and equipment, orders and jobs, human operators, materials, finished and unfinished products),
- Type of approach concerning PPC (e. g. rule-based algorithm, data-driven),
- Characteristics of the approach presented (e. g. decentralised, real-time, robust),
- Types of disturbances considered,
- Relevant previous works of the publication at hand,
- Applied Industry 4.0 technologies.

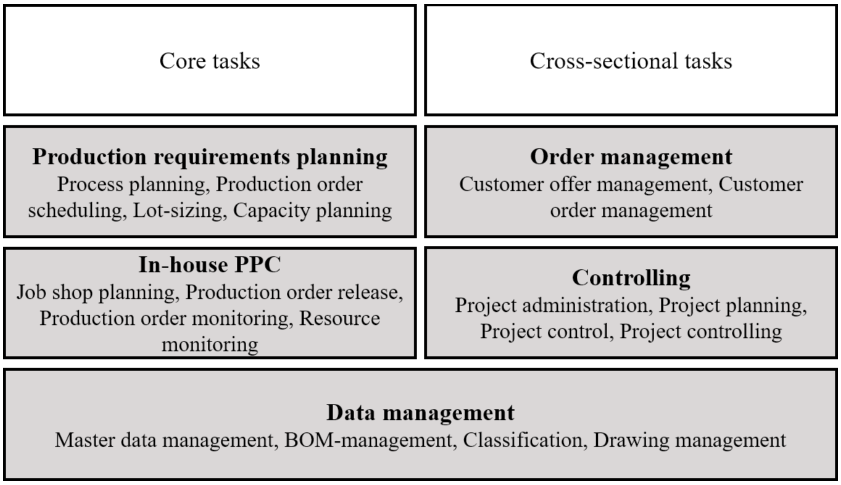

Fig. 2. Considered tasks (bold font) and functions (thin font, below) of the Aachen PPC model [5, modified].

In the second search iteration, it was searched in the remaining databases with the same limits applied as in the first iteration. The other databases' analyses resulted in the following: WoK 737, WISO 1,697, and GoSc 53,423 publications. For the first 200 publications per database, sorted by relevance, the title and abstract have been investigated. After the full-text examination, four publications were sorted out, lacking a connection to Industry 4.0, PPC, or addressing a task of the Aachen PPC model that is not considered in this publication. After the second search iteration has been finished, a reselection of the publications from the first search iteration was carried out, to assure that the results of both iterations follow the same strategy. The result of the selection process is that 48 publications have been included in the qualitative synthesis. Afterwards, one individual conducted an exploratory literature review.

A classification scheme was developed to evaluate the coherence of each reviewed publication with the functions of the Aachen PPC model, which are aligned to the five tasks considered (see Fig. 2). Oriented at [5], these functions were broken down into three components that, if possible, were mutually exclusive. A component represents a low-level activity or a set of actions that contributes to the execution of a function. For each publication, it was checked, how many components of each function are fulfilled by the approach presented. To fulfil means that the considered publication implements the respective component or contributes to the implementation of that component if used in the same PPC system. Fig. 3 shows how an exemplary publication fulfils three components of the function Job shop planning, which is part of in-house PPC. It can be observed that the example publication fulfils two components of Job shop planning. Since it was only possible to break down each function into three components at most, a subjective assignment of a publication to a function was included as another measure of coherence to achieve an ordinal scale of five levels. The scale is also shown in Fig. 3. Including the subjective assignment, a coherence score of three is computed in the example, that is, strong coherence of the exemplary publication with Job shop planning.

Function Task

In-house PPC		
Job shop planning	Component	Score
	Subjective assignment to this function by the author	X
	Ressource utilisation planning (e. g. machine utilisation planning, personell utilisation planning)	X
	Sequence planning	
	Rule-/Knowledge-based job shop planning or simultaneous planning of ressources with optimisation algorithms	X
	0 = No coherence, 1 = Weak coherence, 2 = Neutral coherence, 3 = Strong coherence, 4 = Full coherence	3

Fig. 3. Example of the methodology of the classification scheme for one exemplary function.

3.2. Results

Fig. 4 shows the reviewed publications according to their publication year onto a timeline from 2014-2019. The publications examined on a full-text basis mainly address the task in-house PPC. 33 of 48 publications outline the real-time applicability of their approach (e. g. [18, 19]). In eight of 48 publications the authors describe their approach as dynamic (e. g. [20]) and in six of 48 publications as autonomous (e. g. [21]), adaptive (e. g. [22]), flexible (e. g. [23]), or intelligent (e. g. [24]). Another characteristic outlined in some publications, namely five of 48, is the robustness of the approach presented [23]. 15 of 48 publications outlined a particular scheduling problem of which seven are flexible or hybrid (e. g. [25]), five are a job shop scheduling problem (e. g. [18]) and ten a flow shop scheduling problem (e. g. [26]).

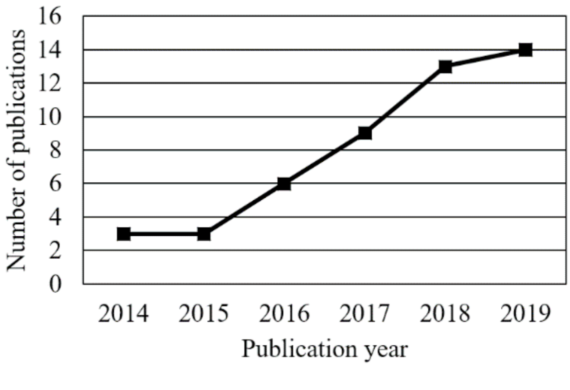

Fig. 4. Number of Publications per Year from 2014-2019.

The reviewed publications employ several Industry 4.0 technologies. [6] and [27] describe these technologies and how they contribute to a CPPS or smart factory. [27] present a hierarchical architecture for a smart factory, which consists of a physical resource layer, network layer, cloud application layer, and terminal layer. To each layer, they assign representative Industry 4.0 technologies. These comprise, e. g., RFID technology, wireless sensor networks, cloud computing, or smart devices for human-computer interaction. [28] presents a reference architecture for a scheduling system. It consists of a system for shop floor data collection and three modules for database management, schedule generation, and a user interface. Fig. 5 combines the two architectures described above into a single architecture for cyber-physical PPC. It shows current Industry 4.0 technologies, deployed for the realisation of a PPC system in a smart factory. To each module of the scheduling system architecture [28], a layer of the smart factory architecture is assigned [27]. Each layer shows the Industry 4.0 technologies currently used for scheduling systems and how they interconnect. At least two publications use each technology out of all reviewed publications. To the most popular Industry 4.0 technologies used belong RFID tags and readers, sensors, smart sensors, and wireless sensor networks. Since a significant part of the publications addressed some type of scheduling problem, the reviewed approaches are classified according to the classification scheme for scheduling problems found in [12], which is extended by the classes policy, instruction systems, MAS and simulation for the remaining approaches.

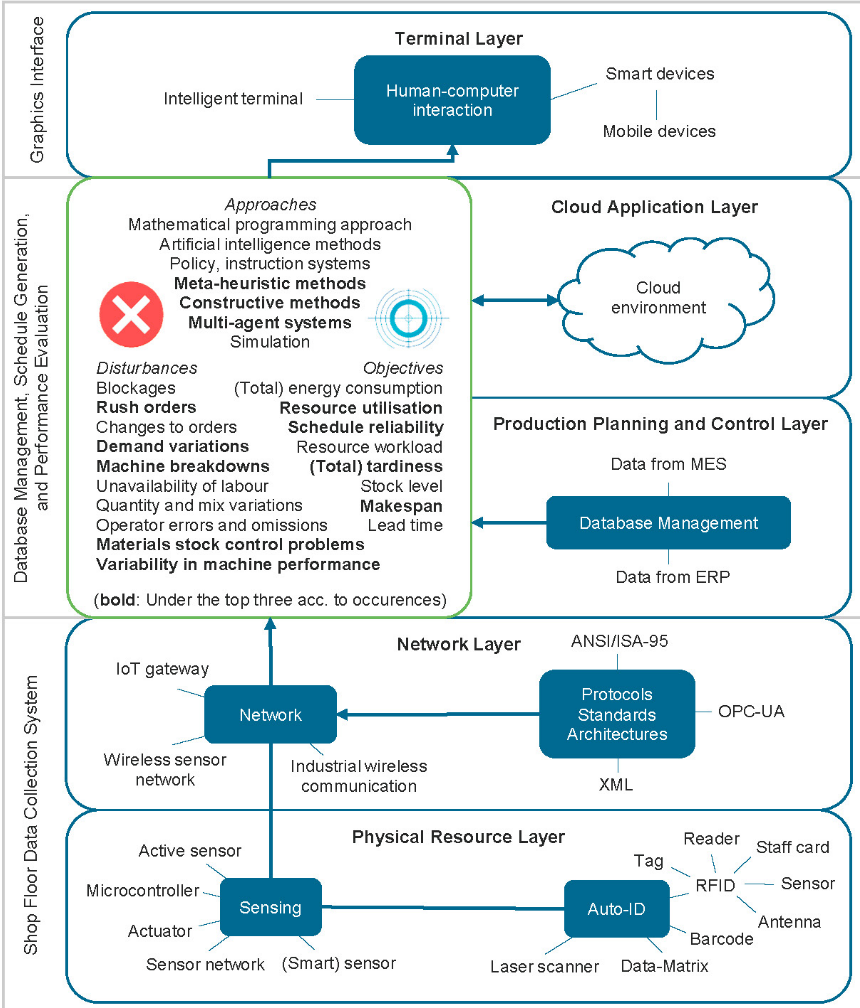

Fig. 5. Cyber-physical PPC architecture.

The identified publications focus on the control of production. In particular, methods and concepts for dealing with disturbances are presented. Therefore, the classification scheme of [29] is applied here to characterise the different types of disturbances, published in the selected publications. Fig. 5 incorporates the various disturbances below the classification of approaches. Out of 70 times in which a disturbance is considered in the reviewed publications, 66% belong to the class of internal disturbances, 30% to downstream disturbances, and 3% to upstream disturbances. An objective function expresses the objectives of each approach reviewed. A classification of all objective functions is also shown in Fig. 5. However, these classes are defined by the authors and are not necessarily mutually exclusive. The most popular approaches, disturbances, and objectives, are highlighted in bold.

Based on the developed classification scheme, Rank order clustering was carried out with the component fulfilment for each publication. The resulting clusters consist of publications that fulfil a specific set of components. Because in the full-text examination, one publication turned out to be a previous work of another, the former is left out in the two cluster analyses. Out of 72 components, 40 components are not fulfilled by any of the reviewed publications, or they represent the subjective assignment, which is excluded in the cluster analysis. Thus 32 components remain for Rank order clustering. Fig. 6 shows the results of Rank order clustering and the classification scheme, which has been reduced to the 32 components. Three clusters can be observed. In the following, the green cluster is called cluster A, the orange one cluster B, and the blue one cluster C. Cluster B is a subset of the components of cluster A.

Components

Publ.	17	10	32	1	29	5	25	24	8	7	16	9	20	3	28	4	26	6	15	23	19	18	30	2	31	11	27	21	12	13	14	22
1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
3	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0	0	1	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0
5	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	1	0
9	1	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	1	0	1	1	1	0	0	0	0	0	0	1	0	1	0
10	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	1	0	0	0	1	1	0	1	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0
13	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	1	1	1	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	1	0
17	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	1	0	1	0	1	0	0	0	1	0	0	0	0	1	1	1	0
18	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	1	0	0	1	1	1	0
19	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	1	1	1	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	1	0	0	1	1	1	0
21	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	1	1	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	1	1	1	0
25	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	1	1	1	1	0
26	0	0	0	0	0	0	1	1	0	1	1	0	1	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	1	1	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1	0	0	0	1
29	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	1
30	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	1	0	1
31	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	1	0	1	1
32	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	1
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	1	1	1
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36	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	1
37	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	1	1	1
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39	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	1
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	1
44	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	1	1
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	1	0	0	0	1	0	0	1	1	1	1	1
46	0	1	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	1	0	1	1	1	1	1
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1

Production requirements planning		No.
Process planning	Issuing of process plans (manufacturing process plans, assembly process plans, line checking plans, …)	1
	Administration of alternative process plans/operation plans (e. g. due to the change of the lot-size, material, capacity utilisation, ...)	2
	Resource assignment to the process plans (Maschines, means/tools for line checking, personell, …)	3
Production order scheduling	Monitoring of production order status	4
	Determination of the different operation times (setup time, processing time, transport times, …)	5
	Backward/forward scheduling	6
Lot-sizing	Quantity bundeling of similar operations	7
	Merging or splitting of production order quantities or operations	8
Capacity planning	Capacity requirements planning on the basis of the production order schedules	9
	Capacity supply planning based on shift plans, day plans, week plans, etc.	10
	Matching of capacity requirements and capacity supply	11
In-house PPC		
Job shop planning	Resource utilisation planning (e. g. machine utilisation planning, personell utilisation planning)	12
	Sequence planning	13
	Rule-/Knowledge-based job shop planning or simultaneous planning of resources with optimisation algorithms	14
Production order release	Availability check of ressources at release date/time	15
	Production order release and the release sequence according to different criteria	16
	Provision of the required resources	17
Production order monitoring	Data processing and overview of target status and actual status of work in progress, quantities and schedule	18
	Derivation of measures for the optimisation of the production execution	19
	Tracing of the production order origin and initiator (e. g. customer)	20
Resource monitoring	Overview of target status and actual status of orders on specific resources, WIP, as well as related maintenance and customer orders	21
	Data processing and overview of machine parameters, breakdowns, condition, ...	22
	Overview of queued orders	23
Order management		
Customer order management	Release of customer orders with all data relevant for the execution in the different departments	24
	Monitoring of customer orders (order status, target and actual progress) and invoicing	25
Project management (Controlling)		
Project control	Reporting of planned and actual schedule (Gantt-charts, critical path method)	26
Project controlling	Reporting and detailed tracking of project cost and changes over time	27
Product data management (Data management)		
Master data management	Implementation of additional information to master data sets	28
BOM-management	Management and selection of alternative BOMs according to selection criteria	29
Classification	Support for the traceability and reusability of material data through classification systems	30
Drawing management	Material master data administration and exchange via ERP-/PPS-, CAD- and EDM-/PDM-Systems	31
	Provision of drawing management functionalities, like drawing attachment to data sets in ERP- or PPS-systems	32

Fig. 6. Rank order clustering of 47 publications (Green: cluster A; orange: cluster B; blue: cluster C).

Within cluster A, three components belong to the function of job shop planning and two to the function of resource monitoring. Within cluster B, three components belong to the function of job shop planning and one to the function of resource monitoring, implying a high similarity of the two clusters. Two components within cluster C belong to the function of production order monitoring and one to the function of resource monitoring.

With twelve publications belonging to cluster A, 15 to cluster B, and 18 to cluster C, cluster C is the largest cluster. However, cluster C has the smallest number of attributes as the cluster sizes get smaller, with an increasing number of attributes (components). Four or more publications still fulfil some components that are not comprised of any cluster. Most of these components belong to the functions of production requirements planning, namely, process planning, production order scheduling, lot-sizing, and capacity planning. The components of the functions within the tasks order management, controlling, and data management are hardly addressed by the reviewed publications, that is, by less than four publications.

Spectral clustering gives three clusters with the scores (coherences) that every publication has for the functions of the Aachen PPC model. Fig. 7 shows the average coherence of each publication with the functions within a cluster that are non-zero. Cluster F represents the largest research stream focusing narrowly on job shop planning and, to a little extend, on process planning, production order monitoring, and resource monitoring. The latter two functions are rather present in cluster F combined with less coherence with job shop planning. Three members in cluster E indicate a sparsely populated but narrowly focussed research stream that focusses on process planning.

The publications assigned to the function of job shop planning subdivide into studies that investigate existing approaches of PPC under Industry 4.0, MAS approaches and approaches solving a scheduling problem with metaheuristic methods, mixed-integer linear programming methods, and rule-based methods. In production order monitoring, the reviewed approaches are heterogeneous. A comparison of different methods, simulation-based production control, instruction systems, or a MAS approach, to name a few, are presented. A common feature that appears in seven of 14 approaches is the definition of events that trigger the actions for controlling or optimising the production execution (e. g. [18, 30]). Also, some of the approaches aim to provide decision support for the human operator as the decision-maker in production control (e. g. [31]).

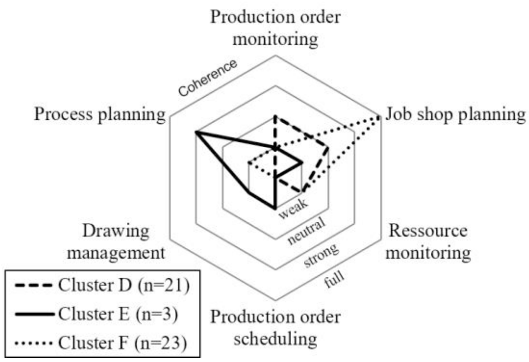

Fig. 7. Spectral clustering: Average coherence of the different clusters with the functions.

4. Future research perspectives and recommended courses of action

The reviewed publications focus on the detailed PPC, that is, the in-house PPC. Merely four publications are assigned to the functions of the task production requirements planning. It is proposed to investigate further how the opportunities and technologies of Industry 4.0 are deployed in this area. Research should be conducted in studying the automated issuing of process plans or the dynamic administration of alternative process plans. As already investigated in [32], methodologies for the estimation and determination of variable processing times should be extended to different areas. Further research should be carried out in how dynamic lot-sizing and quantity bundling can be realised through real-time data and benefit the economic efficiency of production. Based on real-time data availability, it is worth investigating how to improve capacity requirements planning to match capacity demand and supply in a dynamic Industry 4.0 environment.

[2] point out that Industry 4.0 will cause improvements for the planning aspect of PPC; however, that does not fit with the findings of this literature review. In contrast, the reviewed approaches concentrate on production control. Although many publications are classified into job shop planning, it should be noted, that many of the approaches within do not exclusively limit their scope to the activities that are carried out before the production order release. This is underlined by many approaches utilising real-time data from the shop floor, as stated in chapter 3.2 and also with regards to how in-house PPC is described in the Aachen PPC model. The improvement of production control through higher data availability and quality is a match between the authors' outlook and the findings of this publication. The approaches reviewed stand out in high exploitation of the increased data availability and quality gained through Industry 4.0 technologies (see chapter 3.2). Further research activities should be carried out in

improving the production order release, e. g. through developing intelligent or data-driven release criteria and dynamic provision of resources at release time.

Analogously to [12], the results of the present literature review question, if recent research focusses enough on the use of new technologies to solve the job shop problem. As stated in chapter 3.2, a significant part of the reviewed papers presents a particular scheduling problem under the use of Industry 4.0 technologies shown in Fig. 5. Still, this research should be further exploited. That might include the consideration of upstream disturbances like materials quality problems and property variations or supplier production problems resulting in spontaneous unavailability of materials, as several works already consider most of the remaining disturbances. Besides, the possibilities of cloud manufacturing in the context of in-house PPC and scheduling problems should be leveraged in future studies, since they received little attention in the papers reviewed.

The findings of this literature review support the outlooks for adaptive and flexible approaches of PPC under Industry 4.0 in [13] as well as for autonomous, cooperative, intelligent, or robust production systems in [6]. Current approaches for PPC are dynamic, autonomous, adaptive, flexible, intelligent, and robust (see chapter 3.2). A variety of approaches applying evolutionary methods, biology-inspired algorithms, MAS as well as policy and instruction systems, to name a few, was reviewed. Data-driven planning, scheduling, and control of production should be further researched. In this regard, it is also proposed to develop new solutions for supporting the decision-making of human operators in production as a future research direction.

In the present literature review, the supporting tasks of the Aachen PPC model, order management, controlling, and data management received little to no attention. The cluster analyses indicate that these tasks lie out-of-scope of the reviewed literature. Nevertheless, it is proposed to investigate how to involve the customer in the planning, release, and monitoring of real-time manufacturing systems. Real-time information could support a detailed cost tracking that helps to report cost and changes of cost over time and to perform more detailed budgeting. Also, dynamic and intelligent data storage, alternative bill-of-materials, and the influence of a digital twin on drawing management, and how it connects to the PPC represent topics for future research. Finally, as is observable in Fig. 4, research in the area of PPC under Industry 4.0 gained attention over the past years, and a rising trend can be projected for the future.

5. Conclusion

Since 2014, the term Industry 4.0 gained popularity in research and thus influenced the development of concepts for PPC. Recent studies envision a CPPS that can handle high complexity and perform autonomous and intelligent decision-making based on the shop floor's real-time data. The presented exploratory literature review identifies 48 relevant papers based on the findings of two search iterations. These papers are reviewed and classified concerning the Aachen PPC model. Rank order clustering and spectral clustering are carried out to reveal the functions of the Aachen PPC model. The identified functions form the basis for an architecture of cyber-physical PPC, showing Industry 4.0 technologies, current optimisation methods, optimisation objectives, and the management of disturbances. The results are discussed in comparison with the research directions described in previous studies. Unexplored tasks and functions of the Aachen PPC model are identified, and future research directions proposed.

The present contribution is based on a comprehensive classification scheme. Nevertheless, it should be noted that the selection of search terms and the interpretation of the texts is based on an individual assessment. The revelation of unexplored tasks and functions of the Aachen PPC model might have a different outcome if the search term combination is differently parameterised. Therefore, the effects of a different parameterisation and an extended number of reviewed papers will be investigated.

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