# Flexibility dimensions in cyber-physical production systems

**Robin Huwa, Marcus Albrecht, Andreas Leinenbach, Johannes Schilp**

**Angaben zur Veröffentlichung / Publication details:**

Huwa, Robin, Marcus Albrecht, Andreas Leinenbach, and Johannes Schilp. 2024. "Flexibility dimensions in cyber-physical production systems." In *2024 4th International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), 4-6 November 2024, Male, Maldives*, 1–6. Piscataway, NJ: IEEE. https://doi.org/10.1109/iceccme62383.2024.10796674.

*Proc. of the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME 2024)*
*4 - 6 November 2024, Male, Maldives*

# Flexibility Dimensions in Cyber-Physical Production Systems

Robin Huwa
*Chair of Digital Manufacturing*
*University of Augsburg*
Augsburg, Germany
robin.huwa@uni-a.de

Marcus Albrecht
*Chair of Digital Manufacturing*
*University of Augsburg*
Augsburg, Germany
marcus1.albrecht@uni-a.de

Andreas Leinenbach
*Chair of Digital Manufacturing*
*University of Augsburg*
Augsburg, Germany
andreas.leinenbach@uni-a.de

Johannes Schilp
*Chair of Digital Manufacturing*
*University of Augsburg*
Augsburg, Germany
johannes.schilp@uni-a.de

***Abstract*—A key objective in modern and future manufacturing is increasing efficiency and eliminating downtime, even in the face of rapidly changing markets. To achieve this, various concepts and technologies are currently being researched in the context of manufacturing. One of the main topics of research is expanding the flexibility of resources, processes, products and their combination. This would enable and optimize concepts such as cloud manufacturing or equipment-as-a-service. However, in the literature, many authors focus on researching and experimenting with concepts or algorithms without defining flexibility. While the benefits of flexibility are intuitively understandable, often no quantifiable metric or qualitative analysis is proposed. This leads to ambiguities and a lack of comparability between approaches. In this paper, relevant literature and their implicitly covered flexibility dimensions are categorized explicitly along the Product-Process-Resource model. Based on this, an exemplary temporal resource flexibility model and its benefits are discussed. This numerical modeling method can be applied to further define flexibility for simulations or optimization algorithms.**

***Index Terms*—Flexible Manufacturing Systems, Manufacturing Automation, Production Control, Flexibility**

## I. INTRODUCTION

The topic of enabling and expanding flexibility has been gaining importance in manufacturing for decades. Especially since the fourth Industrial Revolution, products in manufacturing are becoming increasingly customizable, with the demand for individualization rising steadily [1]. This requires not only the digitalization of manufacturing, from machine parks to business processes but also its flexibilization. This is one of the key areas of focus in the relevant literature: Legacy production systems are being reworked to expand their ability to react to changes and reschedule accordingly. However, there are various facets of flexibility in current research. This leads to the term being used in many contexts, from managerial to technical. Definitions have been proposed that focus describing on the ability of a system to adapt, react or respond to changes [2]–[5]. These do not, however, quantify flexibility.

In different fields of research, flexibility is numerically modeled. For example in electrical energy systems, the term flexibility of a participating entity, be it a producer or consumer, is defined as the ability of the entity to deviate from its default grid load profile [6]. This can be possible by using for example (battery-based) energy storage systems, limiting electrical consumption or other means. While there are many parameters of the entity in question that influence energy flexibility, its modeling is simple: kilowatt-hours over time.

In this paper, the flexibility dimensions in manufacturing are extracted and categorized along the structure of the Product-Process-Resource (PPR) model, using these definitions [7]:

- *Product*: A thing or substance produced by a natural or artificial process.
- *Process*: Structured set of activities involving various enterprise entities, that is designed and organized for a given purpose.
- *Resource*: Any device, tool and means, excepted raw material and final product components, at the disposal of the enterprise to produce goods or services.

These definitions have been employed in standardized information exchange [8]–[10]. Hence, they are used in this work for the categorization of flexibility. This provides a clear basis for further research on flexibility in manufacturing.

This paper is structured as follows: Section II gives an overview of the main research topics of production systems that deal with flexibility. In Section III, the extracted flexibility dimensions are presented and categorized. In Section IV, an exemplary model for the temporal flexibility of a resource and its benefits is delineated and discussed. In Section V, this paper is concluded and goals for future work are proposed.

## II. IMPLICIT USAGE OF FLEXIBILITY IN LITERATURE

To gain a deeper understanding of the term *flexibility* in the context of manufacturing, this section will present a summary of the prominent research topics and their respective flexibility aspects. It should be noted that other, less directly relevant research topics exist, which are not covered here.

### A. Flexible Manufacturing System

Flexible Manufacturing System (FMS) is an established term that has been used in the past decades. Kaigobadi and Venkatesh [11] define three characteristics of the FMS:

- Potentially independent numerical control machine tools.
- An automated material handling system.
- An overall method of control that coordinates the functions of both the machine tools and materials handling system so as to achieve flexibility.

This definition is still applicable to current research such as Pavel and Stamatescu [12], who create an experimental FMS using robotics, computer vision and further Industry 4.0 technologies, or Pan et al. [13], who create an optimized deadlock-avoiding scheduling algorithm.

The term FMS has evolved to encompass a broader range of applications, including the increasing flexibility of manufacturing systems. Consequently, it is now used in a more diverse manner than the above definition would suggest. For example, Vital-Soto and Olivares-Aguila [14] define the key characteristics of FMSs on a higher abstraction level:

- Adaptability that allows changes and adaptation of processes and production volumes within the pre-defined limits without physically modifying the manufacturing system.
- Responsiveness to changes in products, production technology, and markets.
- Agility to launch new products for new markets and react to change, which is achieved with the help of computer-integrated control and operation of system modules and production schedules.

Related and successive concepts such as *Reconfigurable Manufacturing Systems* and *Smart Manufacturing Systems* have evolved [14] to include new technological capabilities and further research topics. However, all of these definitions allow for various interpretations and do not quantify flexibility.

### B. Flexibility in the Job Shop Scheduling Problem

The Job Shop Scheduling Problem (JSSP) formalizes the problem of scheduling jobs to a workshop. This formalization poses strict constraints within its definition [15]:

- A workshop consists of a fixed set of machines.
- A job consists of an ordered set of multiple operations.
- Job operations are already mapped onto machines.

Based on these assumptions, the following goal is aimed for: *What is the optimal order of operations across all jobs on the machines in the workshop?* In this context, optimality may be defined in terms of overall equipment efficiency, makespan, other metrics or combinations thereof [16]–[18].

A relaxation of the previous definition is found in the Flexible Job Shop Scheduling Problem (FJSSP) [15], [19]–[22]. This removes the constraint that a mapping between job operations and viable machines already exists. Consequently, the problem contains the new goal of finding an optimal mapping, which increases algorithmic complexity.

The above variation of the JSSP however does not cover online changes. While following the current production schedule, events may occur such as machine breakdown or the addition of products. In the Dynamic JSSP, these events are covered and rescheduling of active jobs is considered [23], [24].

In these problem definitions, the concept of flexibility is reduced to the substitutability of resources such as machines. No other kinds of flexibility are considered, leading to a restricted view. However, this restriction makes the solution of the optimization problem computationally manageable. Other variations of this general problem have been proposed, such as those presented in [25], [26], which, however, do not address the issue of flexibility.

### C. Flexibility of Multi-Agent Systems in Manufacturing

Some works about manufacturing employ Multi-Agent Systems (MASs) in their ideas to formulate the production plant of the future [27], [28]. There are significant conceptual changes in how manufacturing should be conducted: The classic approach entails the use of machines with predefined production steps. These are monitored by external software, which mostly aims to notice failures and similar irregularities. This centralized logic should be distributed with logically cohesive functionality grouped and abstracted interaction interfaces between them. This concept is known as MAS, wherein multiple logical agents with general *supply* offers and *demand* goals interact so that the goals are met by the offers.

In the context of production systems, agents manage products and resources (such as machines). Product agents manage manufacturing goals which are declarative, method-agnostic descriptions of the desired part state. Resource agents offer manufacturing skills that may achieve these goals. When singular skills are insufficient, skill composition can be employed for aggregate manufacturing capabilities. Similarly to the FJSSP, the mapping between skills and goals is not defined and has to be determined by the agents, especially given that different skills may achieve the same goal. This MAS concept in manufacturing is illustrated in Fig. 1, with product and resource agents and also the relationship between their goals and skills. The process plan of a product would hence comprise the sequence of negotiated skills that collectively achieve all product goals. A basic method for finding a feasible sequence is exploring a path in the topology of all possible resource skill concatenations until all product goals are met.

Using MASs necessitates some assumptions about the machines in a cyber-physical production system. In addition to enabling the reading of status information and other pertinent attributes to verify the machine's capabilities, the system must also facilitate remote adaptation of the machine's control logic. Furthermore, the machine must possess settings that facilitate

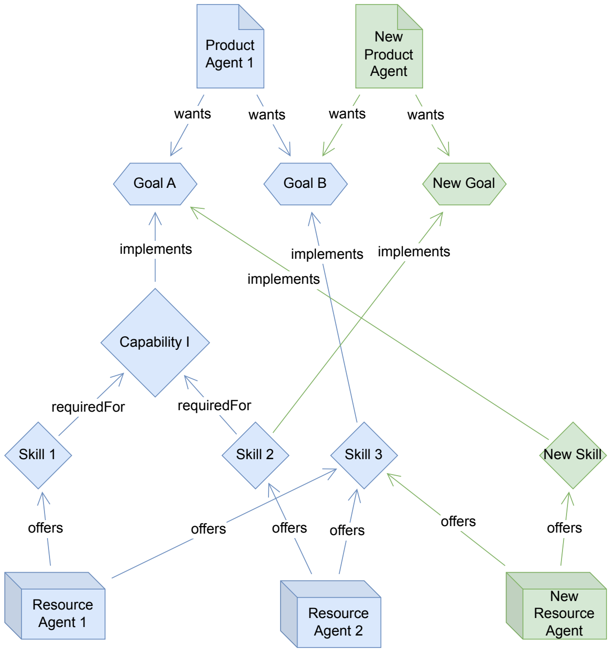

Fig. 1. Visualization of a multi-agent system in manufacturing. At the top product agents are depicted with their production goals, while at the bottom resource agents with their skills and aggregate capabilities. This architectural approach decouples product design from resource functionality.
*Image: Chair of Digital Manufacturing.*

diverse operational modes, a feature that may not be present in legacy devices. At the very least, modifying the processing speed may permit energy savings or just-in-time machining so that the machine is synchronized with the subsequent production steps. However, much more flexibility is expected of future machines, products and also processes to enable flexible and alternative-rich manufacturing. For new resources, the concept of Plug & Produce [29]–[31] is key for seamless integration. In this concept, resources automatically register themselves into the overall production facility, with self-described states and skills that can be automatically integrated into manufacturing processes or MASs.

In addition to the theoretical approaches to the creation and management of MASs, there has been progress in the digitization of products and resources in analogous ways. Specifically, standardization and virtualization efforts such as the Asset Administration Shell (AAS) [29], [32], Open Platform Communications Unified Architecture (OPC UA) NodeSets [33] or the IndustryFusion Process Data Twin (PDT) [34] propose product- and resource-centric digital representations as a basis for possible further virtual interaction. Upon comparison of these approaches with the concept of MASs, striking similarities emerge. Asset-centric digital twins of either AAS or PDT are analogous to agents. The PDTs or the resource AASs as well as OPC UA NodeSets describe the parameters, capabilities and skills of machines, similar to resource agents. The product AASs contain various forms of descriptions regarding the product, similar to product agents.

Although not explicitly designated as MASs, those technologies exhibit several of the defining characteristics and should therefore be considered in the general discussion. These decentralized architectures are, in essence, implementations of the software design principle called *low coupling, high cohesion* [35]. Hence, the aforementioned approaches share a common benefit: Instead of managing a monolithic block of production logic, subsystems become less interdependent and more self-contained. In practice, this results in clusters of functionality or knowledge that can be adapted and exchanged individually, with minimal impact on other parts and parties of the system. This decentralization therefore enables important advantages for all involved parties.

## III. FLEXIBILITY TAXONOMY

When using the term flexibility in the manufacturing context, different authors make different implicit assumptions about its meaning. They therefore expand different dimensions of flexibility. These can be grouped into three categories according to the PPR model, which is shown in Table I.

Some authors enable *product* flexibility by decoupling the product design and definition from the production process [27], [36], [37]. This is achieved by either introducing autonomous product agents or adapting the process and resource logic to allow for different products to be managed without re-implementation for each change.

The majority of authors expand *process* flexibility by enabling alternative paths of products in the production process that are chosen dynamically depending on the production plant resources and logistics state [5], [13]–[24], [28], [38]–[46].

Finally, some authors investigate the concept of *resource* flexibility, which involves enabling machines, that otherwise would solely be pre-programmed, to dynamically change their programming so that their skills and capabilities can be adapted more quickly to new tasks [2], [4], [12], [47]–[49].

The aforementioned literature has identified various operational and tactical flexibility types. *Operational* in this context refers to short-term reactions, while *tactical* signifies the medium-term planning and scheduling of a system [3]. Some of the authors discuss flexibility at a higher level of abstraction such as strategic flexibility [3], which refers to the long-term planned changeability of a system. This is not the focus of this paper. In the following, these flexibility dimensions will be defined and categorized according to the PPR model. See Fig. 2 for a visualization. For products, the following dimensions have been found:

- Temporal: Variable time-to-finish.
- Operations: Alternative production steps for the same goal.
- Mix: Alternative product family versions. [36]

For processes, the following dimensions have been found:

- Routing: “Number of alternative paths a part can take through the system in order to be completed.” [3]
- Sourcing: “Ability to find another supplier for each specific component or raw material.” [3]
- Order: Independent operations may be reordered.

TABLE I.
Table of sources and their covered flexibility dimensions sorted into the product-process-resource model. Flexibility measures are marked $\mathcal{M}$, metrics and measurements $\mathcal{F}$.

| Source | Flexibility | | |
|---|---|---|---|
| | Product | Process | Resource |
| [27] | $\mathcal{M}$ | | |
| [36] | $\mathcal{M}$ | | |
| [37] | $\mathcal{M}$ | | |
| [5] | | $\mathcal{M}$ | |
| [13] | | $\mathcal{M}$ | |
| [14] | | $\mathcal{F}$ | |
| [15] | | $\mathcal{M}$ | |
| [16] | | $\mathcal{M}$ | |
| [17] | | $\mathcal{M}$ | |
| [18] | | $\mathcal{M}$ | |
| [19] | | $\mathcal{M}$ | |
| [20] | | $\mathcal{M}$ | |
| [21] | | $\mathcal{M}$ | |
| [22] | | $\mathcal{M}$ | |
| [23] | | $\mathcal{M}$ | |
| [24] | | $\mathcal{M}$ | |
| [28] | | $\mathcal{M}$ | |
| [38] | | $\mathcal{M}$ | |
| [39] | | $\mathcal{M}$ | |
| [40] | | $\mathcal{M}$ | |
| [41] | | $\mathcal{M}$ | |
| [42] | | $\mathcal{M}$ | |
| [43] | | $\mathcal{F}, \mathcal{M}$ | |
| [44] | | $\mathcal{M}$ | |
| [45] | | $\mathcal{M}$ | |
| [46] | | $\mathcal{M}$ | |
| [2] | | | $\mathcal{F}$ |
| [4] | | | $\mathcal{M}$ |
| [12] | | | $\mathcal{M}$ |
| [47] | | | $\mathcal{M}$ |
| [48] | | | $\mathcal{M}$ |
| [49] | | | $\mathcal{M}$ |
| [3] | $\mathcal{F}$ | $\mathcal{F}$ | $\mathcal{F}$ |

- Temporal: Variable execution time(s).
- Scale: Variable product throughput.

For resources, the following dimensions have been found:

- Temporal: Variable start and end time of jobs.
- Batch: Concurrent jobs on one resource.
- Parallel: Independent usage of different parts of the resource.
- Material: Variable materials may be handled by the resource.
- Quality: Variable processing quality to enhance other goals (e.g. production speed/time).

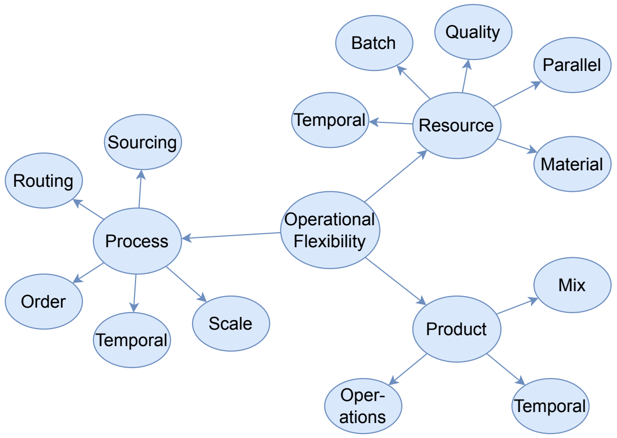

Fig. 2. Visualization of flexibility dimensions in literature in the three categories product, process and resource. These short- to mid-term flexibilities enhance manufacturing in logically separate dimensions.
*Image: Chair of Digital Manufacturing.*

Although this list of dimensions is not exhaustive, it provides an overview of the flexibility dimensions that are typically possible. In most cases in manufacturing, it is to be expected that specialized forms of flexibility will be required, depending on the intricacies of the entities that are being considered. Therefore, the flexibility dimensions must be modeled in a way that is appropriate for the currently considered case.

The existing literature lacks a discussion of modeling approaches. The sources in Table I research measures and metrics of flexibility, but none of the analyzed works model flexibility numerically. A model of this nature could be employed in further simulations of the production system.

## IV. Flexibility Modeling Discussion

For flexibility to be utilized on an operational or tactical level, it must be quantifiable. Analogous to the definition of flexibility in electrical energy systems [6], the following definition of flexibility modeling is proposed: An entity, whether a resource, process or product, must be capable of numerically modeling its possible deviations from the default state. This would permit the simulation of flexibility, which could then be validated in the context of specific scenarios.

For example, a simple scenario of temporal resource flexibility is depicted in Fig. 3. Resource $r$ is used by process $x$ to create product $p$. Critically in this scenario, process $x$ uses resource $r$ within the interval $[t_1, t_2] \in T$, the time dimension. However, a process $x_2$ for a product $p_2$ requires resource $r$ in a time slot overlapping the time interval $[t_1, t_2]$. This conflict can be resolved by the temporal flexibility of the resource $r$ which allows for the rescheduling of the time interval $[t_1, t_2]$ for process $x$. This is marked in orange in Fig. 3.

The limits of the temporal flexibility are constrained by the internal state and previously scheduled usages of resource $r$. This temporal flexibility is not only limited by the capabilities of resource $r$, but also interacts with the flexibility of process $x$. If process $x$ has scheduled some steps for its product within the time interval directly preceding $[t_1, t_2]$, it is not possible to

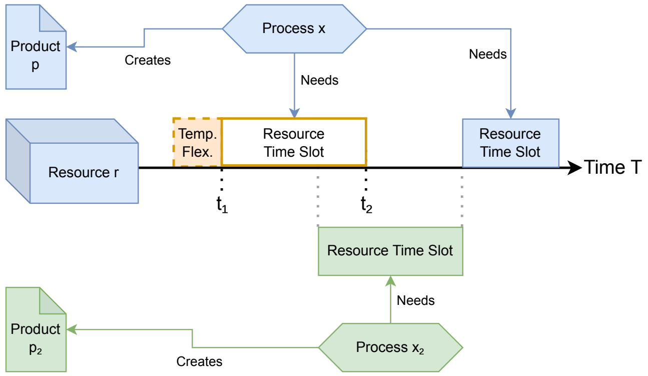

Fig. 3. Visualization of a basic model of temporal resource flexibility. The resource time slot $[t_1, t_2]$ may be rescheduled using temporal flexibility to allow another resource time slot of another process to be executed afterward. *Image: Chair of Digital Manufacturing.*

reschedule the use of resource $r$. In such a case, the schedule of process $x$ and the relevant other resources can be iterated to find a solution using other flexibilities.

To compute accurate values of the flexibility limits for usage time slots of resource $r$, it is necessary to model the influencing variables of it and the products and processes that utilize it. These may include the internal state of the machine, the delays incurred by changing the planned schedule, or previous and following schedules. Furthermore, hardware or process safety concerns limit the offerable flexibility.

This illustration of flexibility modeling demonstrates the inherent interrelatedness of products, processes, and resources, which is also exhibited by their other flexibility dimensions. This introduces algorithmic complexities in the simulation and evaluation of flexibility use cases. Nevertheless, numerical modeling enables the precise prediction of the adaptability of a production plant during execution. As more flexibility dimensions are modeled, the potential for adapting overall production to accommodate new incoming products, altered processes, or failed resources increases.

## V. CONCLUSION

This paper presents the common implicit usages of the term flexibility in manufacturing using various exemplary research topics. Afterward, those works are categorized using the product-process-resource model, and their researched flexibility dimensions are stated explicitly. Finally, the temporal flexibility of a resource is discussed as an example of the benefits of flexibility modeling. This work proposes a numerical modeling concept to methodically expand the technical use of flexibility in, for example, dynamic optimization algorithms.

Future work may include defining and numerically modeling the temporal and additional flexibility dimensions, as well as utilizing them in simulations. Benchmark scenarios can be defined to analyze the benefits. Once the advantages have been validated in the virtual realm, connecting flexibility modeling with modern production control approaches using for example digital twins can be explored.

## REFERENCES

[1] R. K. Sikhwal and P. R. N. Childs, "Product design for mass individualisation for industrial application," in *2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pp. 674–680, ISSN: 2157-362X. [Online]. Available: https://ieeexplore.ieee.org/document/8289976

[2] A. Sajjad, W. Ahmad, S. Hussain, and R. M. Mehmood, "Development of innovative operational flexibility measurement model for smart systems in industry 4.0 paradigm," vol. 10, pp. 6760–6774, conference Name: IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/document/9666888

[3] C. Anthony, M. Zakariae, and B. Armand, "Measuring and identifying appropriate levels of flexibility: A novel approach and use case in the automotive industry," in *2023 3rd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)*, pp. 01–06. [Online]. Available: https://ieeexplore.ieee.org/document/10152909

[4] O. Salunkhe and A. Fast-Berglund, "Increasing operational flexibility using industry 4.0 enabling technologies in final assembly," in *2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, pp. 1–5. [Online]. Available: https://ieeexplore.ieee.org/document/9198630

[5] P. Schönsleben, "Techniques for planning and control dependent on different types of flexibility," vol. 56, no. 1, pp. 451–454. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0007850607001096

[6] D. Danner, R. Huwa, and H. De Meer, "Multi-objective flexibility disaggregation to distributed energy management systems," *ACM SIGENERGY Energy Informatics Review*, vol. 2, no. 2, pp. 1–12, 2022.

[7] A. Cutting-Decelle, R. Young, J. Michel, R. Grangel, J. Le Cardinal, and J. Bourey, "ISO 15531 MANDATE: A product-process-resource based approach for managing modularity in production management," vol. 15, no. 2, pp. 217–235, publisher: SAGE Publications Ltd STM. [Online]. Available: https://doi.org/10.1177/1063293X07079329

[8] A. F. Cutting-Decelle, J. L. Barraud, B. Veenendaal, and R. I. Young, "Production information interoperability over the internet: A standardised data acquisition tool developed for industrial enterprises," vol. 63, no. 8, pp. 824–834. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0166361512001297

[9] J. XIAO, N. ANWER, A. DURUPT, J. LE DUIGOU, and B. EYNARD, "Standardisation focus on process planning and operations management for additive manufacturing," in *Advances on Mechanics, Design Engineering and Manufacturing : Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing (JCM 2016), 14-16 September, 2016, Catania, Italy*, B. Eynard, V. Nigrelli, S. M. Oliveri, G. Peris-Fajarnes, and S. Rizzuti, Eds. Springer International Publishing, pp. 223–232. [Online]. Available: https://doi.org/10.1007/978-3-319-45781-9_23

[10] A. L. Fraga, M. Vegetti, and H. P. Leone, "Semantic interoperability among industrial product data standards using an ontology network:," in *Proceedings of the 20th International Conference on Enterprise Information Systems*. SCITEPRESS - Science and Technology Publications, pp. 328–335. [Online]. Available: http://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0006783303280335

[11] M. Kaighobadi and K. Venkatesh, "Flexible manufacturing systems: An overview," vol. 14, no. 4, pp. 26–49, publisher: MCB UP Ltd. [Online]. Available: https://doi.org/10.1108/01443579410056029

[12] M.-D. Pavel and G. Stamatescu, "Flexible manufacturing system for enhanced industry 4.0 and industry 5.0 applications." [Online]. Available: https://www.grigorestamatescu.com/files/dcoss24_1.pdf

[13] Y.-L. Pan, C.-W. Tai, C.-Y. Tseng, and J.-C. Huang, "Enhancement of computational efficiency in seeking liveness-enforcing supervisors for advanced flexible manufacturing systems with deadlock states," vol. 10, no. 7, p. 2620. [Online]. Available: https://www.mdpi.com/2076-3417/10/7/2620

[14] A. Vital-Soto and J. Olivares-Aguila, "Manufacturing systems for unexpected events: An exploratory review for operational and disruption risks," vol. 11, pp. 96 297–96 316, conference Name: IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/document/10237110

[15] K. A. G. Araújo, E. G. Birgin, and D. P. Ronconi, "Models, constructive heuristics, and benchmark instances for the flexible job shop scheduling problem with sequencing flexibility and position-based learning effect." [Online]. Available: http://arxiv.org/abs/2403.16766

[16] Z. Chen, Y. Laili, L. Zhang, and L. Wang, “A trans-ptr-nets based transfer optimization method for multi-objective flexible job shop scheduling in IIoT,” pp. 1–1, conference Name: IEEE Internet of Things Journal. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10511280

[17] S. Wei, H. Tang, X. Li, D. Lei, and X. V. Wang, “An improved memetic algorithm for multi-objective resource-constrained flexible job shop inverse scheduling problem: An application for machining workshop,” vol. 74, pp. 264–290. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0278612524000542

[18] Y. Sang, J. Tan, and W. Liu, “Research on many-objective flexible job shop intelligent scheduling problem based on improved NSGA-III,” vol. 8, pp. 157 676–157 690, conference Name: IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/document/9179804

[19] N. Álvarez Gil, R. Rosillo, D. De La Fuente, and R. Pino, “A discrete firefly algorithm for solving the flexible job-shop scheduling problem in a make-to-order manufacturing system,” vol. 29, no. 4, pp. 1353–1374. [Online]. Available: https://link.springer.com/10.1007/s10100-020-00701-w

[20] Z. A. Abd Alhussain and L. S. Hassan, “A review on elitist ant system algorithm and applications in flexible job scheduling problem,” vol. 4. [Online]. Available: https://bjeps.alkafeel.edu.iq/journal/vol4/iss2/5

[21] A. Bagheri Verkiani, P. F. Sheikhlari, and S. H. A. Rahmati, “Energy-conscious flexible job shop scheduling using metaheuristic algorithms,” vol. 5, no. 1. [Online]. Available: https://doi.org/10.22034/jaisis.2024.423324.1075

[22] D. Huang, H. Zhao, L. Zhang, and K. Chen, “Learning to dispatch for flexible job shop scheduling based on deep reinforcement learning via graph gated channel transformation,” pp. 1–1, conference Name: IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10489964

[23] A. Tariq, S. A. Khan, W. H. But, A. Javaid, and T. Shehryar, “An IoT-enabled real-time dynamic scheduler for flexible job shop scheduling (FJSS) in an industry 4.0-based manufacturing execution system (MES 4.0),” vol. 12, pp. 49 653–49 666, conference Name: IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10488407

[24] S. Lu, Y. Wang, M. Kong, W. Wang, W. Tan, and Y. Song, “A double deep q-network framework for a flexible job shop scheduling problem with dynamic job arrivals and urgent job insertions,” vol. 133, p. 108487. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0952197624006456

[25] G.-G. Wang, D. Gao, and W. Pedrycz, “Solving multiobjective fuzzy job-shop scheduling problem by a hybrid adaptive differential evolution algorithm,” vol. 18, no. 12, pp. 8519–8528, conference Name: IEEE Transactions on Industrial Informatics. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9751346

[26] M. Mahmoodjanloo, R. Tavakkoli-Moghaddam, A. Baboli, and A. Bozorgi-Amiri, “Flexible job shop scheduling problem with reconfigurable machine tools: An improved differential evolution algorithm,” vol. 94, p. 106416. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1568494620303562

[27] I. Kovalenko, E. C. Balta, D. M. Tilbury, and K. Barton, “Cooperative product agents to improve manufacturing system flexibility: A model-based decision framework,” vol. 20, no. 1, pp. 440–457, conference Name: IEEE Transactions on Automation Science and Engineering. [Online]. Available: https://ieeexplore.ieee.org/document/9737280

[28] M. H. Jabeur, S. Mahjoub, C. Toublanc, and V. Cariou, “Optimizing integrated lot sizing and production scheduling in flexible flow line systems with energy scheme: A two level approach based on reinforcement learning,” vol. 190, p. 110095. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S036083522400216X

[29] X. Ye, J. Jiang, C. Lee, N. Kim, M. Yu, and S. H. Hong, “Toward the plug-and-produce capability for industry 4.0: An asset administration shell approach,” vol. 14, no. 4, pp. 146–157, number: 4. [Online]. Available: https://ieeexplore.ieee.org/document/9299411/

[30] C. Eymüller, J. Hanke, A. Poeppel, and W. Reif, “Towards self-configuring plug & produce robot systems based on ontologies,” in *2023 9th International Conference on Automation, Robotics and Applications (ICARA)*. IEEE, pp. 23–27. [Online]. Available: https://ieeexplore.ieee.org/document/10126075/

[31] C. Eymuller, J. Hanke, A. Hoffmann, A. Poeppel, C. Wanninger, and W. Reif, “Towards a real-time capable plug & produce environment for adaptable factories,” in *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA )*. IEEE, pp. 1–4. [Online]. Available: https://ieeexplore.ieee.org/document/9613729/

[32] T. A. Abdel-Aty, S. Galparoli, E. Negri, and L. Fumagalli, “A methodology for the design and creation of asset administration shell for manufacturing systems,” 2022.

[33] A. Perzylo, S. Profanter, M. Rickert, and A. Knoll, “Opc ua nodeset ontologies as a pillar of representing semantic digital twins of manufacturing resources,” in *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2019.

[34] A. Leinenbach, M. Wagner, F. Oettl, and J. Schilp, “The process data twin for digitized production,” 2024, to be published.

[35] J. Eder, G. Kappel, and M. Schrefl, “Coupling and cohesion in object-oriented systems,” 1994.

[36] A. A. Neto, E. Ribeiro Da Silva, F. Deschamps, L. A. Do Nascimento Junior, and E. Pinheiro De Lima, “Modeling production disorder: Procedures for digital twins of flexibility-driven manufacturing systems,” vol. 260, p. 108846. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0925527323000786

[37] R. Andersen, A. Napoleone, A.-L. Andersen, T. D. Brunoe, and K. Nielsen, “A systematic methodology for changeable and reconfigurable manufacturing systems development,” vol. 74, pp. 449–462. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0278612524000748

[38] L. Cheng, Q. Tang, L. Zhang, and C. Yu, “Scheduling flexible manufacturing cell with no-idle flow-lines and job-shop via q-learning-based genetic algorithm,” vol. 169, p. 108293. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360835222003564

[39] Z. Zhu, H. Xu, Y. He, Z. Pan, M. Zhang, and C. Jian, “A DRL-based online real-time task scheduling method with ISSA strategy.” [Online]. Available: https://link.springer.com/10.1007/s10586-024-04426-2

[40] D. Erzse, A. Nilgesz, and P. Harfas, “A production planning solution for industrial IoT-enabled manufacturing.”

[41] M. Spamer and L. Bam, “Modelling manufacturing process flexibility: A systematic review,” in *2022 IEEE 28th International Conference on Engineering, Technology and Innovation (ICE/ITMC) & 31st International Association For Management of Technology (IAMOT) Joint Conference*, pp. 1–9. [Online]. Available: https://ieeexplore.ieee.org/document/10033295

[42] K. Tliba, O. Penas, T. M. L. Diallo, R. Ben Khalifa, N. Ben Yahia, and J.-Y. Choley, “Model based systems engineering approach for the improvement of manufacturing system flexibility,” in *2020 21st International Conference on Research and Education in Mechatronics (REM)*, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/9313871

[43] S. Mayer, L. F. D. P. Sotto, and J. Garcke, “The elements of flexibility for task-performing systems,” vol. 11, pp. 8029–8056, conference Name: IEEE Access. [Online]. Available: https://ieeexplore.ieee.org/document/10024253

[44] L. Tiacci and A. Rossi, “A discrete event simulator to implement deep reinforcement learning for the dynamic flexible job shop scheduling problem,” p. 102948. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1569190X24000625

[45] J. Song, C. Miao, and F. Kong, “Uniform-machine scheduling problems in green manufacturing system.” [Online]. Available: https://www.aimsciences.org//article/doi/10.3934/mfc.2024020

[46] A. Zhu, P. Pauwels, E. Torta, H. Zhang, and B. De Vries, “Data linking and interaction between BIM and robotic operating system (ROS) for flexible construction planning,” vol. 163, p. 105426. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580524001626

[47] G. Fragapane, D. Ivanov, M. Peron, F. Sgarbossa, and J. O. Strandhagen, “Increasing flexibility and productivity in industry 4.0 production networks with autonomous mobile robots and smart intralogistics,” vol. 308, no. 1, pp. 125–143. [Online]. Available: https://link.springer.com/10.1007/s10479-020-03526-7

[48] G. Azizpour, M. Ashourpour, and K. Johansen, “Enhancing manufacturing flexibility through automation packaged solution (APS): A case study approach,” in *Advances in Transdisciplinary Engineering*, J. Andersson, S. Joshi, L. Malmsköld, and F. Hanning, Eds. IOS Press. [Online]. Available: https://ebooks.iospress.nl/doi/10.3233/ATDE240167

[49] D. Etz, T. Frühwirth, and W. Kastner, “Flexible safety systems for smart manufacturing,” in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, pp. 1123–1126, ISSN: 1946-0759. [Online]. Available: https://ieeexplore.ieee.org/document/9211905