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Angaben zur Veröffentlichung / Publication details:

Huwa, Robin, Marcus Albrecht, Andreas Leinenbach, and Johannes Schilp. 2025. "Towards modelling flexibility limits in cyber-physical production systems." In *Proceedings of the Conference on Production Systems and Logistics: CPSL 2025*, edited by David Herberger and Marco Hübner, 83–92. Offenburg: publish-Ing. https://doi.org/10.15488/18858.

CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2025

7th Conference on Production Systems and Logistics

Towards Modelling Flexibility Limits In Cyber-Physical Production Systems

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Abstract

In the context of cyber-physical production systems, the term "flexibility" is typically employed in an intuitive and implicit manner. It is uncommon for proposals that quantify the flexibility of production systems, and even then, only by measuring certain general aspects top-down. However, as flexibility is becoming increasingly crucial for contemporary and future systems in both production and logistics, it must be regarded as a value- and data-driven resource for comprehensive system analysis.

This paper presents a generic model for quantifying the flexibility of entities within a production system, comprising processes, products, and resources. These three entities represent the fundamental elements of any production system, which is therefore conceptualised and presented as a multi-agent system. The flexibility model of an entity is defined in terms of two sets of constraints. Firstly, the inherent limits of the solution space of any singular entity must be considered. These limits are formed by factors such as the limitations of the software or hardware in use. Secondly, the boundaries of the flexibility space are defined by the interactions between entities. Such constraints may be formed, for example, by entity interdependencies or preparatory measures for the interaction. By employing these types of constraints, which are both rule- and data-driven, this generic methodology can describe the resulting numerical flexibility space of individual entities. This paper focuses on temporal flexibility models, which are the most universally applicable flexibility dimension, and considers their implementation for products, processes, and resources.

Keywords

Production Planning & Control; Flexibility; Mathematical Modelling; Smart Manufacturing; Simulation; Factory Planning; Production Systems; Manufacturing Automation; Constraint Modelling

1. Introduction

The pace of change in industrial demands is accelerating, as are the timescales for product releases. At the same time, expectations regarding product customisation are rising. These trends are driving the current 4th and 5th industrial revolutions, which are characterised by a shift from mass production towards personalised production. This contrasts with the still viable mindset of static mass production, which is embedded vertically through every level of the production system, down to the machines.

Hardware and machine setups in production settings are, in most cases, designed with mass production in mind. The only notable exception to this is additive manufacturing. Currently, a variety of approaches and methodologies are being developed with the aim of adapting and expanding existing production lines in order to manufacture additional goods [1–4]. However, no generalised numerical approach based on exploiting inherent capabilities and flexibilities of machines and processes and products involved has been proposed, as found in previous research [5].

DOI: https://doi.org/10.15488/18858
ISSN: 2701-6277

From the perspective of optimisation, an additional issue arises. In general, production is mono-dimensionally optimised for production costs, focusing on the current or pre-planned product range. This optimisation approach for mass production has its legacy in previous environmental settings such as static consumer demands and slow product release cycles. Furthermore, costs remain one of the important quantifiable metrics in production, whereas generally terms such as adaptability, changeability and flexibility remain qualitative at best. Therefore, these dimensions of production systems cannot be optimised or compared quantitatively, but they will become important for production (re-)planning and control with planned or unplanned changes in the product portfolio. Based on these premises, the following research questions are posed in this paper:

- *Can flexibility in production systems be formulated in the form of the inherent flexibility of its entities as numerical models?*
- *How do these models interface, interrelate and interdepend numerically during production?*

The subsequent definition of the proposed numerical modelling approach, which answers these questions, will offer a foundation for further evaluatory analyses of the flexibility of production systems.

The paper is structured as follows: Section 2 presents the necessary background information the successive sections are based on. Section 3 elaborates upon the abstract simulation scenario for the employment of the numerical flexibility models. The interactions of the latter are explained in Section 4. In Section 5, the computation of numerical flexibility limits is defined. The final Section, 6, provides a conclusion to this paper and an overview of planned future work.

2. Background

The following section introduces the requisite background information for the subsequent sections. It provides a summary of the two topics of the flexibility terminology in industry and the product-process-resource model.

2.1 Flexibility Terminology in Industry

As has been demonstrated in previous research [5–7], the term *flexibility* is frequently employed in an industrial context with an intuitive and qualitative meaning. In some instances, terms such as adaptability or changeability are employed in lieu of flexibility. The latter term is employed in an implicit manner for the description of production systems or components of it, such as processes, technologies or machines.

Adaptability, however, has been defined reciprocally with flexibility. In contrast to flexibility, which focuses on (both voluntary or involuntary) changes which are managed by the capabilities of the production system, adaptability deals with influences and effects outside of its limitations [8]. The latter term is often used in the context of the green transformation, holistic production network analysis and similar large-scale examinations. In these contexts, high production system adaptability is a prime factor to improve upon green, sustainable and other overarching goals for the wider industrial setting [8–12]. However, the terminological differences and distinctions between flexibility and adaptability are in general not internationally recognized. As explained above, these terms often are used in similar contexts [13–15].

However, given the increasing importance of this concept in the context of evolving production demands, there is a clear need for a common definition. Infrequently, authors put forth a top-down, a posteriori measurement formula for flexibility, which must remain as generic as possible to encompass the full spectrum of potential flexibility aspects [2, 16–18]. Research also indicates that there are numerous bottom-up dimensions of flexibility to be investigated, based on the capabilities of the entities involved in production [2, 5]. Nevertheless, no bottom-up, numerical modelling of flexibility has been proposed in the field of production, although in general a lot of research in this field has been conducted [6, 7].

2.2 Product-Process-Resource Model

To categorise the constituent elements of production systems in a manner that is both coherent and universally defined, the Product-Process-Resource Model [19] is employed in the following sections. These three categories encompass the principal aspects of production systems and are defined as follows:

- Product: "A thing or substance produced by a natural or artificial process." [19]
- Process: "Structured set of activities involving various enterprise entities, that is designed and organised for a given purpose." [19]
- Resource: "Any device, tool and means, excepted raw material and final product components, at the disposal of the enterprise to produce goods or services." [19]

These definitions provide a robust foundation for further elaborations on flexibility within these different categories in the industrial context, as they have been utilized successfully previously [20–22].

3. System Architecture for Flexibility Models

To determine the most appropriate design for the numerical flexibility models, it is first necessary to define the intended usage environment. The interactions between the model and the environment, as well as between individual models form the fundamental requirements for the models themselves. In the following, the usage environment is defined and after that the individual components thereof.

3.1 Multi-Agent Production System

As proposed by other authors [23, 24], a multi-agent system is an appropriate means of modelling a production environment in its most generalisable and abstracted form. In accordance with the aforementioned Product-Process-Resource Model, the multi-agent production system $S_P \supseteq \{P, X, R\}$ comprises differing agents of three distinct kinds of entities, namely products $p \in P$, processes $x \in X$ and resources $r \in R$. The interaction of product and resource agents is illustrated in Figure 1 and discussed in detail in the following sections.

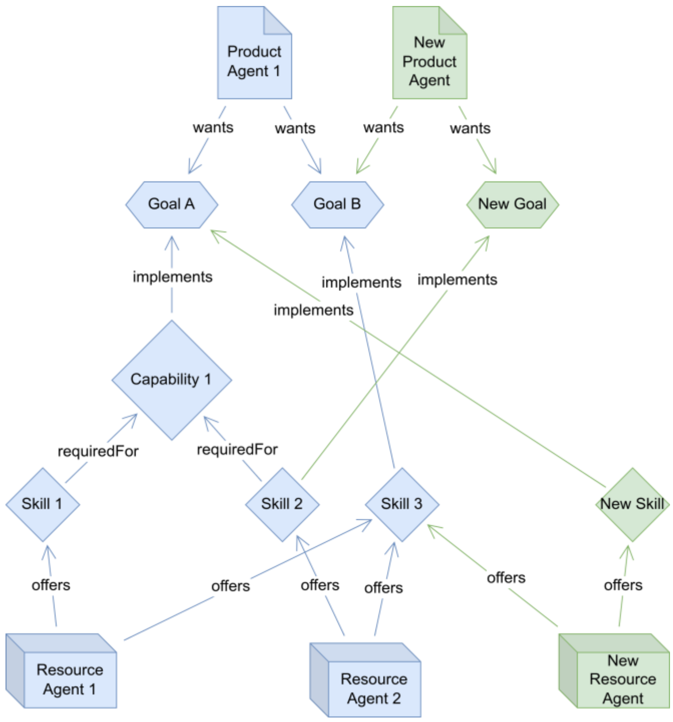

Figure 1: Visual representation of the potential mapping relationships within a multi-agent system between product agents with their defined goals and resource agents with their transformative skills. Not shown here: Process agents, which manage sequences of interactions between multiple product agents and resource agents.

The main benefit of this system architecture is its ability to decouple resource capabilities, product design and process settings. In most cases within the industrial sector, products are designed and manufactured with a specific focus on the capabilities of the available resources and production processes. The use of a multi-agent system architecture as an abstraction layer serves to break up the aforementioned tight coupling, thereby inherently allowing for flexibility that is not afforded by current approaches.

In short, a product agent is defined by given production goals for the product. The aforementioned goals delineate the intended final state of the product. In contrast, a resource agent is defined by the production steps, or skills, it offers, which transform the current state of a given input product into a new output state, utilising available materials and tools. A process agent manages the sequence of transformative steps between product and resource agents, thereby ensuring a feasible mapping between product goals and resource offers. The following section provides a detailed description of these agents.

3.2 Product Agent

A product agent describes its product $p \in P$ using goals $(\alpha_1^p, \ldots, \alpha_{n \in \mathbb{N}}^p)$ which are formulated in a manner that is independent of the production technique. Consequently, in this abstract view of production, a product is not described by production steps but by its desired end state which the production process has to achieve. These goals may describe shape, weight, material, colour as well as any other relevant attribute of the product. In general, the goals $(\alpha_1^p, \ldots, \alpha_{n \in \mathbb{N}}^p)$ are formulated as strict equations or (possibly half-open) tolerance intervals.

The design does not elucidate which sequence of production steps is responsible for achieving the desired product outcomes. This is done to facilitate the pursuit of alternative production processes, rather than focusing on optimising product creation along a single pathway. Nevertheless, the realisation of the product goals is contingent upon the availability of existing resources.

3.3 Resource Agent

A resource agent in the multi-agent system manages a resource $r \in R$, which is described by its capabilities in terms of offer-able skills, or transformative functions $(\beta_1^r, \ldots, \beta_{l \in \mathbb{N}}^r)$. These functions describe production steps that take processes $x \in X$ and products $p \in P$ as input (e.g. $\beta_1^r(x_1, p_1)$), transform and finally return those. It is not necessary for the number of inputs and outputs to be equivalent, for example for material joining techniques. These transformations may be concatenated until the product and process goals are fulfilled. However, this necessitates a process agent for management.

3.4 Process Agent

A process agent is responsible for the management of the production schedule, which entails the ordered mapping between product goals and resource transformations. Additionally, the process agent exhibits its own process goals $(\gamma_1^x, \ldots, \gamma_{m \in \mathbb{N}}^x)$. The latter are meta-goals pertaining to the production process, such as deadlines, cost limits etc., which do not influence the final state of the product directly. Process goals may be either hard or soft constraints, which may be subject to algorithmic optimisation during the creation and adaptation of the production schedule. To optimise the process, it is assumed that a comparative ordering or score function o for the image of $\gamma_{m \in \mathbb{N}}^x$ exists.

The production schedule comprises logically and temporally ordered interactions $i \in I$ between products and resources. A $1{:}N$-relationship holds between processes and products. The actual sequence of mappings between product and resource agents is realised and managed by the process agent. This includes fulfilling the product end state goals $(\alpha_1^p, \ldots, \alpha_{n \in \mathbb{N}}^p)$ at the conclusion of the production schedule, as well as adhering to the process goals $(\gamma_1^x, \ldots, \gamma_{m \in \mathbb{N}}^x)$ throughout the schedule, by employing the existing transformations $(\beta_1^r, \ldots, \beta_{l \in \mathbb{N}}^r)$ offered by resources. Moreover, the process in question generally adheres to optimisation strategies regarding overall production costs. These strategies may not be solely based on direct monetary considerations but may also consider other factors such as energy consumption and total production time.

3.5 Interaction of Agents

An interaction $i \in I$ between entities is defined as a tuple $(p_{n_1 \in \mathbb{N}}, \ldots, p_{n_2 \in \mathbb{N}}, x_{m \in \mathbb{N}}, \beta^r_{l \in \mathbb{N}}, [t_s, t_f])$ which describes the previous, active or planned interaction instance between the products, the process and the transformative function of the resource in a time interval $[t_s, t_f] \subset T$ with t_s, the start time, and t_f, the finish time. The management of these interactions and their logical and temporal ordering is the responsibility of the directly involved process agent. The following section outlines the methodology for calculating the flexibility of interactions, based on the aforementioned definitions.

4. Interaction of Flexibility Models

Having established the context and usage setting, we may now proceed to introduce the flexibility of this system. The aforementioned decoupling of products, processes and resources naturally gives rise to flexibility, namely the possibility of feasible system deviation from the planned state. However, in contrast to the approaches described in related work, this flexibility can be quantified along a number of different dimensions [5]. To illustrate, temporal flexibility is selected as the most illustrative and applicable flexibility dimension. The temporal flexibility afforded by the system can be employed to adapt existing production schedules, for example, to allow the execution of alternative production schedules in parallel.

This is visualised in Figure 2. Process x_1 manages the production of product p_1, and therefore plans an interaction i_1 with resource r at time interval $[t_s, t_f]$. When another process x_2 requires an interaction i_2 with resource r for its product p_2, a scheduling issue arises due to the temporal overlap between i_1 and i_2. However, as i_1 has enough temporal flexibility (marked in orange) to reschedule to an earlier time interval, enough availability can be gained after i_1 to enable the scheduling of i_2.

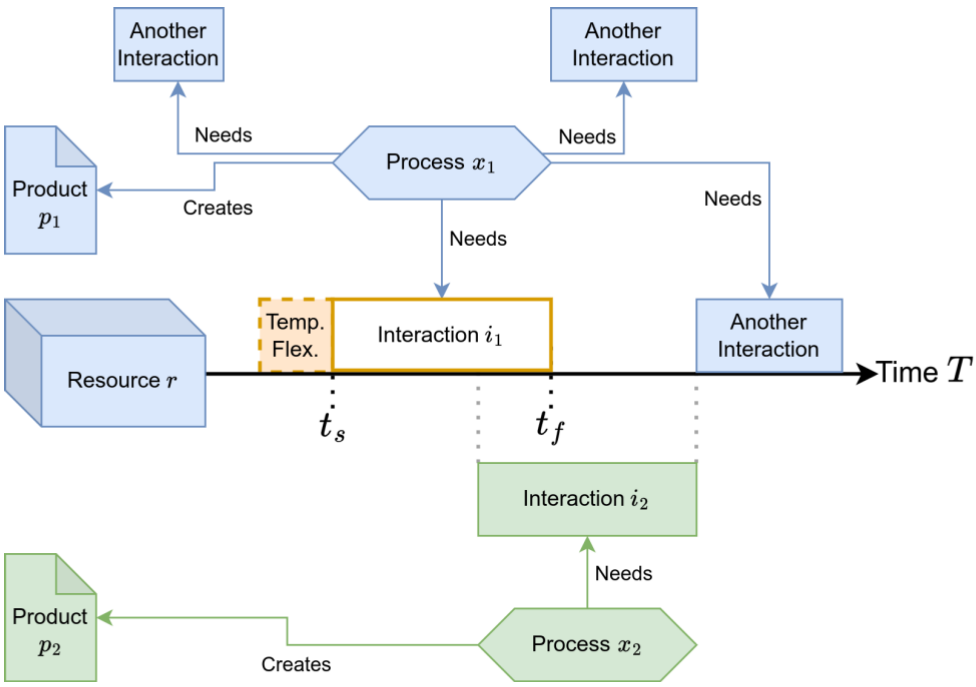

Figure 2: The (re-)scheduling of interactions of products, processes and resources illustrated in a temporal-flexibility-requiring example.

Although the utility of temporal flexibility in the aforementioned example is evident, the boundaries of this flexibility remain unclear. Nevertheless, because of the fact that this multi-agent system has been formulated numerically, it is possible to accurately compute and predict the available flexibility limits of agent interactions.

5. Flexibility Computation

The flexibility definition presented in the following is based on the following assumption: *Given no contradictory information, the entity is flexible.* The extent of flexibility is constrained by two factors: the inherent solution space boundaries of the entity in question and the reciprocal limitations resulting from interactions between entities.

5.1 Entity Solution Space

The solution space of an entity represents the fundamental limit to its flexibility. In the case of resources, such as machines, tools or workers, the aforementioned limits are readily comprehensible and are represented by the transformative functions $(\beta_1^r, \ldots, \beta_{l\in\mathbb{N}}^r)$. Furthermore, the concept of solution space limitation can be applied to the modelling of products and processes. The end state description using different product goals $\left(\alpha_1^p, \ldots, \alpha_{n\in\mathbb{N}}^p\right)$ limits the final shape of the product, which must be achieved during production in accordance with the process goals $(\gamma_1^x, \ldots, \gamma_{m\in\mathbb{N}}^x)$. It is these very limits that define the solution space of individual entities.

5.2 Interaction Flexibility Space

The accurate flexibility space of an interaction must exist within the set of the intersected solution spaces of the entities involved in a production process. Moreover, the remaining flexibility space of an entity is further constrained by interactions with other entities. To illustrate, a resource utilised within a timeslot $\left[t_s, t_f\right] \subset T$ may be operating at maximum capacity, thereby exhibiting the greatest degree of limitation and minimal flexibility within that particular time slot. Consequently, interactions impose more stringent constraints on the flexibility of interactions than merely considering the solution spaces of the entities involved.

Moreover, temporal flexibility may be constrained prior to and subsequent to the designated time interval due to the necessity of undertaking setup or clean-up activities, such as machine tool alterations or warm-up procedures. The rule-based enforcement of local consistency thus further restricts temporal flexibility around the aforementioned timeslot.

5.3 Nth-Order Flexibility Computation

To compute the base flexibility of an interaction, it is sufficient to compute the intersection of the solution spaces of the entities in question, as well as to review the flexibility limits imposed by immediately (temporally or logically) related interactions of the participating entities, as illustrated in Figure 3.

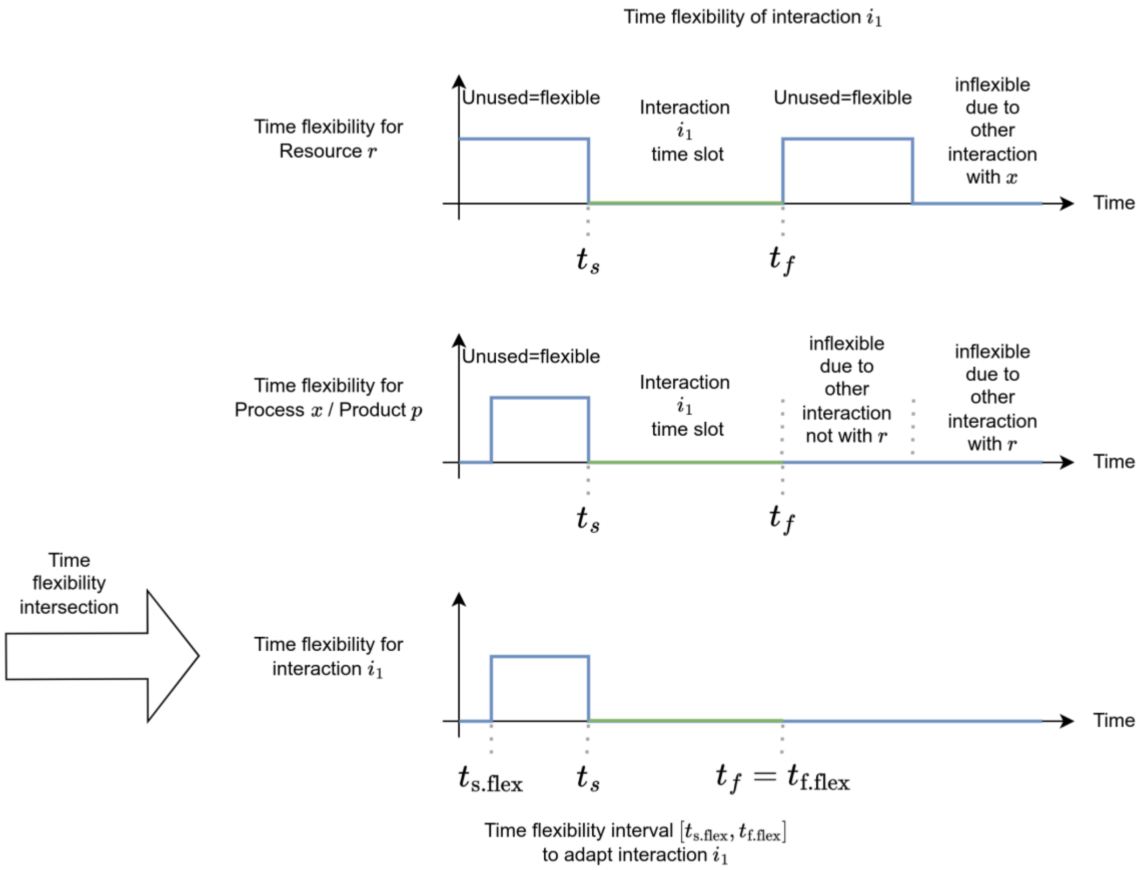

Figure 3: The temporal flexibility of the interaction i of Figure 2 visualised as the intersection of the temporal flexibility of resource r and process x / product p.

The computation of flexibility $f_d(i)$ of an interaction $i \in I$ is highly dependent on the flexibility dimension d in question. For example, the temporal flexibility $f_{\text{temp}}(i)$ takes the in i given time interval $[t_s, t_f] \subset T$ and the participating entities $(e_1, \ldots, e_{n\in\mathbb{N}})$, finds all temporally close interaction time intervals of these entities directly surrounding $[t_s, t_f]$. Based on that information, $f_{\text{temp}}(i)$ computes the interval $[t_{s.\text{flex}}, t_{f.\text{flex}}] \supseteq [t_s, t_f]$ so that the temporal deviation of i within that time interval $[t_{s.flex}, t_{f.flex}]$ is feasible and does not negatively influence any other production schedule. This is illustrated in Figure 3. It should be noted, however, that this is merely one potential definition of the computation of a flexibility dimension for an interaction. In general, the computation of the maximally possible deviation limit is inherently dependent on the flexibility dimension in question.

The computation of $f_d(i)$ exhibits different possible levels of computational depth. This is because the flexibility of interactions is, in general, cumulative relative to the sequential relationship within a production schedule. For example, given three sequentially related interactions $i_{-1}, i_0, i_1 \in I$ with time intervals $[t_s^{i_{-1}}, t_f^{i_{-1}}], [t_s^{i_0}, t_f^{i_0}], [t_s^{i_1}, t_f^{i_1}] \in T$, it is possible that the First-Order temporal flexibility $f_{\text{temp}}^1(i_0)$ as computed in the paragraph above is non-existent due to the flexibility limits $[t_{s.flex}^{i_0}, t_{f.flex}^{i_0}] = [t_s^{i_0}, t_f^{i_0}]$. This might be possible when there are no temporal gaps between the interactions, meaning that $t_f^{i_{-1}} = t_s^{i_0} \wedge t_f^{i_0} = t_s^{i_1}$ holds.

However, if i_{-1} and i_1 themselves are temporally flexible, then that can be exploited by i_0. So, given $t_{s.flex}^{i_{-1}} \leqslant t_s^{i_{-1}}$ and $t_f^{i_1} \leqslant t_{f.flex}^{i_1}$ from the individual First-Order temporal flexibility limits $f_{\text{temp}}^1(i_{-1})$ and $f_{\text{temp}}^1(i_1)$, the result of the Second-Order temporal flexibility $f_{\text{temp}}^2(i_0)$ in this special case is:

$$\left[t_{s.flex}^{i_0}, t_{f.flex}^{i_0}\right] = \left[t_s^{i_0} - \left(t_s^{i_{-1}} - t_{s.flex}^{i_{-1}}\right), t_f^{i_0} - \left(t_f^{i_1} - t_{f.flex}^{i_1}\right)\right] \quad (1)$$

Analogously, other cases, for example those involving some First-Order temporal flexibility available for i_0, can be computed.

Similarly, deeper Nth-Order flexibility computations $f_d^3(i), \ldots, f_d^\infty(i)$ for a flexibility dimension d of an interaction i are definable. With each additional depth, the solution search space is increased by including more entities in the computation. In the special case of Maximal Flexibility $f_d^\infty(i)$, each interaction and entity linked by the process sequence in the production schedule is taken into account recursively.

6. Conclusion

This paper presents a general concept for the development of production systems incorporating flexibility models. The abstract multi-agent system architecture for modelling production systems is outlined, with a particular focus on the individual product, process and resource agents, as well as their interactions. In this context, the concept of numerical flexibility is elucidated and exemplified with temporal flexibility.

The proposed approach demonstrates that flexibility need not remain a qualitative description of individual machines, technologies or production plants; it can be formalised into a rule- and value-driven evaluation of production systems and their components. Once validated to be operative, these quantitative descriptors can become a valuable tool for production (re-)planning and control. This tool can then be employed to evaluate the production schedule in terms of its tolerance of internal or external changes. These changes may be external regulatory, environmental or market-induced influences, or they may be internal, for example machine failures, new product variants or process optimizations. With the proposed modelling approach, the available flexibility can be quantified for further evaluation approaches.

However, the proposed theoretical model has not been validated in laboratory or field experiments. It remains to be evaluated how practical it may be under real-life conditions. One issue is that current manufacturing setups do not facilitate flexibility due to the focus on streamlined, cost-optimized mass production. Furthermore, each component of the setup in question has to be modelled accurately to maximize its potential, in short a digital twin for flexibility. Further research will be done to assess the requirements of the physical production system setup to enable effective flexibility modelling, and how different approaches, such as matrix production, constitute significant factors and influences.

Having outlined and demonstrated the numerical concept of flexibility models with examples, the logical subsequent steps are to extend this to encompass other dimensions of flexibility in interactions and to apply this modelling to more complex and realistic production scenarios. Nevertheless, the results of this study prompt further research questions that will be addressed in subsequent investigations:

- *Can these models be aggregated to quantitively describe the total flexibility of the production line, the machine park, or the production plant?*
- *Which decentralised strategies can be applied to the multi-agent production system architecture to optimise the interrelated interactions of various product, process and resource agents utilising flexibility?*

Acknowledgements

This paper has been created in the context of the AI-Production-Network, which in turn has been enabled and supported by the Hitech Agenda of the Bavarian State Ministry of Education, Science and the Arts.

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Biography

Robin Huwa (*1998) holds a position as a research associate at the Department of Digital Manufacturing at the University of Augsburg since 2023, researching production process virtualization concepts such as cloud manufacturing and equipment-as-a-service.

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