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Ontology-based production planning under the consideration of system robustness

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Abstract

Volatile markets and high customer requirements regarding schedule reliability increase the relevance of robust production planning. To achieve robustness in planning, system-inherent buffers are used. Buffers include resource capacities that are kept free to respond to changes. Targets other than achieving the production plan are not considered, so a trade-off between reliability and the further development of the manufacturing process is not possible. This paper presents a new approach for production planning based on robustness analysis that enables a multi-criteria optimization. An information system enables the company-specific design of the robustness analysis.

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1. Introduction

Due to dynamic effects caused by an increasingly volatile environment and global markets, as well as increasing demands with regard to product individualisation, current planning and scheduling methods are reaching their limits [1]. In order to create adaptable and therefore flexible processes, future planning and scheduling methods must be able to handle increasing complexity and react to new events within a reasonable timeframe [2]. These short-term decisions take no account of long-term targets. One opportunity to include long-term targets is the system-inherent robustness of a manufacturing system. In this article, robustness is defined as an attribute that describes the maximum deviation from the target behaviour of a manufacturing system with it still being possible to achieve short-term production targets [3]. In the presented approach, so-called robustness radii are used to integrate long-term targets into production planning. Short-term targets set boundary conditions for the integration of long-term targets. The approach allows the pursuit of several targets simultaneously. Through the development of a standardized information system, the approach becomes transferable and can be embedded in existing data infrastructures.

2. Current technology

2.1. Robustness

The concept of robustness or the ability of a system to be robust is defined in various ways throughout existing literature. The definitions differ in the consideration of disturbances and their resulting influence. Robustness is defined as a property of a system which makes it possible to maintain a planned state even if the behaviour of the system components and the system environment changes [3]. There are different approaches to integrate and measure robustness (see [4], [5], [6]). In the following, the examined approach used in this paper is briefly presented. For the measurement of robustness, Ali et al. introduce the approach of robustness radii [7]. These robustness radii describe the degree of deviation that a

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disturbance parameter π_j can exhibit before predefined performance indicators Φi are violated. To determine the robustness radii, a disturbance parameter, such as the availability of a machine, is changed gradually and the course of the performance indicator, for example the output, is recorded. System-specific tolerance limits ($\beta_i^{max}, \beta_i^{min}$) are set as performance indicators. Within the tolerance limits, the system functions in a stable planned state.

Nomenclature

Φi	i-th Performance indicator
i, j	Index of a subgroup
π_j	j-th Disturbance parameter
r(Φi, π_j)	Robustness radius
β_i^{max}	Upper tolerance limit
β_i^{min}	Lower tolerance limit
$\rho(\phi, \pi_j)$	Aggregated robustness radius

The robustness radius with respect to a performance indicator is mathematically defined by equation 1. If the robustness radius of a disturbance parameter is determined with regard to different performance indicators, equation 2 is used [7].

$$r(\phi_j, \pi_j) = \pi_j : \left(f_{ij}(\pi_j) = \beta_i^{min}\right)$$

$$\vee^{min}\left(f_{ij}(\pi_i) = \beta_i^{max}\right) \left\|\pi_j - \pi_j^0\right\|_2 \qquad (1)$$

$$\rho(\phi, \pi_j) = \min_{\Phi_i \in \Phi}\left(r(\phi_j, \pi_j)\right) \qquad (2)$$

Ali et al. divides the procedure of robustness analysis into four steps [7]:

1. Definition of performance indicators and their tolerable deviations.
2. Definition of disturbance parameters against which the robustness of the system is to be investigated.
3. Modelling of the effects of disturbance parameters on the performance indicators via a function.
4. Calculation of the robustness radii and their aggregation.

Stobrawa et al. confirmed the applicability of the robustness analysis for the continuous flow manufacturing [3]. A standardised interpretation of the robustness analysis is not performed. Therefore, the transferability to different manufacturing systems and target systems is limited. In addition, the further application in order to achieve long-term targets is addressed only as a prospect. The results of the robustness analysis are not integrated into a scheduling method.

2.2. Ontology

In order to produce a transferable and automated method for robustness analysis, a systematic structuring of a manufacturing system and its associated data is necessary. Ontologies enable error-free data managements [8]. The structure makes a high information content possible. An ontology is divided into classes and subclasses to assign instances (which represent concrete objects or properties). The connections between classes and instances describe properties (so-called object properties). Data properties describe the relationships of classes and instances with concrete data values. In this way, attributes such as the actual availability of a machine can be stored in the ontology.

In the field of production planning and control, different ontologies which divide manufacturing systems into their components already exist. The Core Manufacturing Simulation Data (CMSD) standard [9] offers such an ontology. The standard includes an information system that facilitates the exchange of manufacturing data between a simulation environment and other information systems used in manufacturing. This makes it possible to develop event-based methods for production planning and control independently of the manufacturing system [9]. Ontologies are not explicitly used to integrate robustness. In some cases, attributes are used solely to address uncertainties, for example, by describing the wear of a tool. Another field of application is the installation of non-linear work plans [6]. Resources are assigned to the respective production process and presented as alternatives depending on the process chain. Existing ontologies do still not include disturbance parameters and performance indicators for long-term targets. Therefore, it is not possible to design a robustness analysis automatically based on a given long-term target. Currently, only manual assignments are possible regarding the disturbance parameter's as well as the component's assignment for the analysis.

2.3. Multi-criteria optimization

In order to integrate long-term targets into production scheduling by means of robustness analysis, it is necessary to understand the production system as a multi-target system. In such systems a potential compromise for a predefined set of targets is attempted. In contrast to traditional approaches, multi-objective optimisations do not pursue an objective one-dimensional function which should be minimised or maximised. To define boundary condition for the system to pursue further sub-targets, the targets are prioritised. Such multi-objective systems are already used to improve dispatching rules [10]. The established rules were optimised with regard to two targets: the lead time with its distribution and the order completion. An iterative procedure is followed, which allows an optimisation of different combinations by trial and error. Long-term targets are not included. The approaches currently used, do not allow any variation of the quality requirements considered. They are only transferable to a limited extent for companies who want to evaluate their planning solutions with regard to other targets.

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3. Concept for ontology-based production planning under the consideration of system robustness

A robustness analysis of the manufacturing system can be used to integrate long-term manufacturing targets into planning and scheduling. However, no method exists which standardizes it transferable for every company. In particular, there is no feedback of the robustness results into the planning method to facilitate the pursuit of long-term targets. This gap is closed by the developed concept. The concept is based on the approach of examining the influence of disturbance parameters on the defined performance indicators by performing a material flow simulation. As performance indicators, data likewise the overall performance of the manufacturing system (for example output and lead time) is used. On a component level, the disturbance parameters are defined (for example, availability and processing time) [3]. In order to perform a target-oriented robustness analysis, data processing of production targets is necessary. The target tracking implements disturbance parameters in the production. These disturbance parameters have to be derived before the actual robustness analysis takes place and have to be assigned to the manufacturing components on that these affects. A new information system is established to prepare this information for the robustness analysis. The information system specifies possible performance indicators and disturbance parameters, depending on targets and the manufacturing components. In order to use the simulation-based robustness analysis, the predefined performance indicators and disturbance parameters are divided into data, which can be mapped in the simulation. In the second step, a concept is presented for the method's integration into scheduling, allowing a prioritised integration of several targets. The planning method traces the variation possibilities back to targets and defines the values for target tracking. If, for example, it is determined that the processing time of a workstation can be changed by one minute without violating the short-term performance indicators, this time can be used to achieve further training targets. An employee, who needs longer to complete the operation due to his or her level of knowledge, can be assigned to the workstation. However, due to the number of repetitions, the employee experiences a learning process and thus improves in the long term. The allocation of resources (rescheduling of the distribution of employees) would change in the production plan.

3.1. Ontology-based information system

The information system structures the data required for the robustness analysis. The information includes the assignment of disturbance parameters to long-term targets, the assignment of performance indicators to short-term targets and the assignment of disturbances to the components of the manufacturing system. By extending an ontology, which is already used for the general description of manufacturing systems, with disturbance parameters and performance indicators, a standardised selection range for company-specific robustness analyses can be created. In order to integrate the disturbance parameters and performance characteristics in the simulation, the information system contains data that can be integrated in an event-based simulation. To identify this data, the Electronic Product Code Information Service (EPCIS) is used. The standard describes events in the simulation, such as the change of a disturbance parameter, via so-called attributes [1]. These attributes represent event data that describe an event considering the following questions: what, where, when and why. Such event data represent, for example, timestamps recorded when an event occurs and is ended.

Any change caused by a disturbance parameter can be recorded using this data. At the same time, each performance indicator can be calculated using this event's data. For example, the lead time can be calculated via the booking points (where) and time stamp (when) [1]. In order to realise the robustness analysis for the integration of long-term targets into the scheduling, this data must be aggregated. Therefore, the information system describes the relationship between long-term targets, like the further training of an employee, and associated disturbance parameters, like the employee performance level. Likewise, the aggregation of performance indicators, like the output, to the short-term targets, like efficiency. Additionally, the information system aggregates disturbance parameters to the components of the manufacturing system (see Fig. 1).

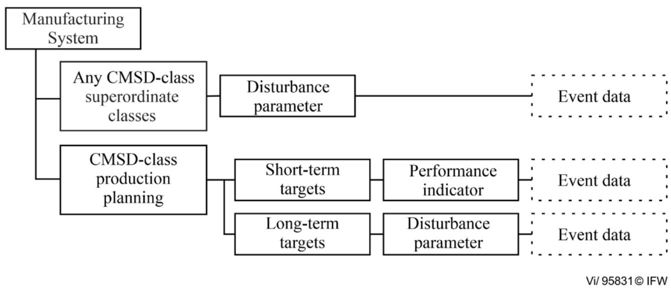

Fig. 1. CMSD based Ontology for the robustness analysis

In this way, it is possible to identify which disturbance parameters are induced in the manufacturing system when pursuing a long-term target and by means of which components these influences can be implemented in the simulation model. The identified disturbance parameters can be assigned to the components that the upper section of the ontology show in Fig. 1. This is done by examining the characteristics of each component that influences the overall performance and defining them in the form of event data. For example, the machine availability is a risk of interruption which influences the output of the manufacturing system. The ontology-based Core Manufacturing Simulation Data (CMSD) standard is used for the aggregation for the information system.

By dividing the manufacturing system into the following classes:

- Layout,
- Part information,
- Support,
- Resource information,
- Production operations and
- Production planning,

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any type of production data can be assigned. Thus, all components of a production system can be mapped. As shown in Fig. 1 CMSD based Ontology for the robustness analysis disturbance parameters are assigned to each component in the manufacturing system. This is necessary in order to allocate the disturbance parameters induced by the long-term target tracking regarding the components in the following. The ontology is designed with the ontology editor Protégé and stored in RDF/XML file format for OWL ontologies. The ontology is accessed with the Owlready2 package for Python. Here it is represented as an RDF graph in the form "subject - predicate - object". For example, the class of long-term Targets has a subclass employee qualification (subject in the RDF triple), which is linked via the predicate "possesses" to the disturbance parameter "processing time" (object in the RDF triple). The information that the processing time is changed during further qualification at the workplace can be mapped. The triples are specified using the Uniform Resource Identifier (URI), which is assigned by the editor when the ontology is built. The RDF graph is stored in a database with the format SQLite3 on the RAM.

3.2. Embedding in production planning

The simulation-based robustness analysis requires a production schedule which has been established in advance. This production schedule can be set up using logistic priority rules.

In a first step, the user selects the long-term targets from the information system to be integrated (see Fig. 2). In this context, the selected long-term targets are periodized. After a first user input and with the help of the information system, the disturbance parameters relevant for the achievement of the targets are selected from the subclass of long-term targets. Second, the user selects tolerance limits for the short-term performance indicators which should not be violated. For these short-term performance indicators, company-specific tolerance limits are defined. With the selected disturbance parameters, a one-dimensional robustness analysis is performed in which only one disturbance parameter is manipulated. The variation of the disturbance parameter can be specified by the user. Otherwise, a standardised step size and a predefined value range is adapted depending on the value of the disturbance parameter (see the first decision block in Fig. 2). The robustness radii from this first investigation represent the initial solution space for the following multi-criteria investigation. For this purpose, the value ranges of the disturbance parameters which are determined to be robust are used as solution space for the multi-objective optimisation. If the system does not show any recognisable robustness against the disturbance parameters of a target, the target is excluded from the optimisation.

Within the multi-criteria optimisation, the targets are planned according to their priority. For this purpose, additional disturbance parameters of further targets are included in each iteration. Each iteration step includes a robustness analysis. The sequence determines the periodization of the targets by the user. The disturbance parameters for which it is still possible to fulfil the range of the short-term performance indicators are transferred to the next iteration step. In each iteration, the range of variation of the disturbance parameters is reduced, which still allows the achievement of the range of the short-term performance indicators. If the short-term performance indicators are no longer achieved with the standard values of the disturbance parameter during integration, the optimisation discontinue the planning of further long-term targets (see second decision block in Fig. 2). These values and the initial values can be used to define the scope for target tracking. For this purpose, these are aggregated to form the targets. According to the results of the multi-criteria robustness analysis, the resource allocation and the calculated times in the production plan are adjusted.

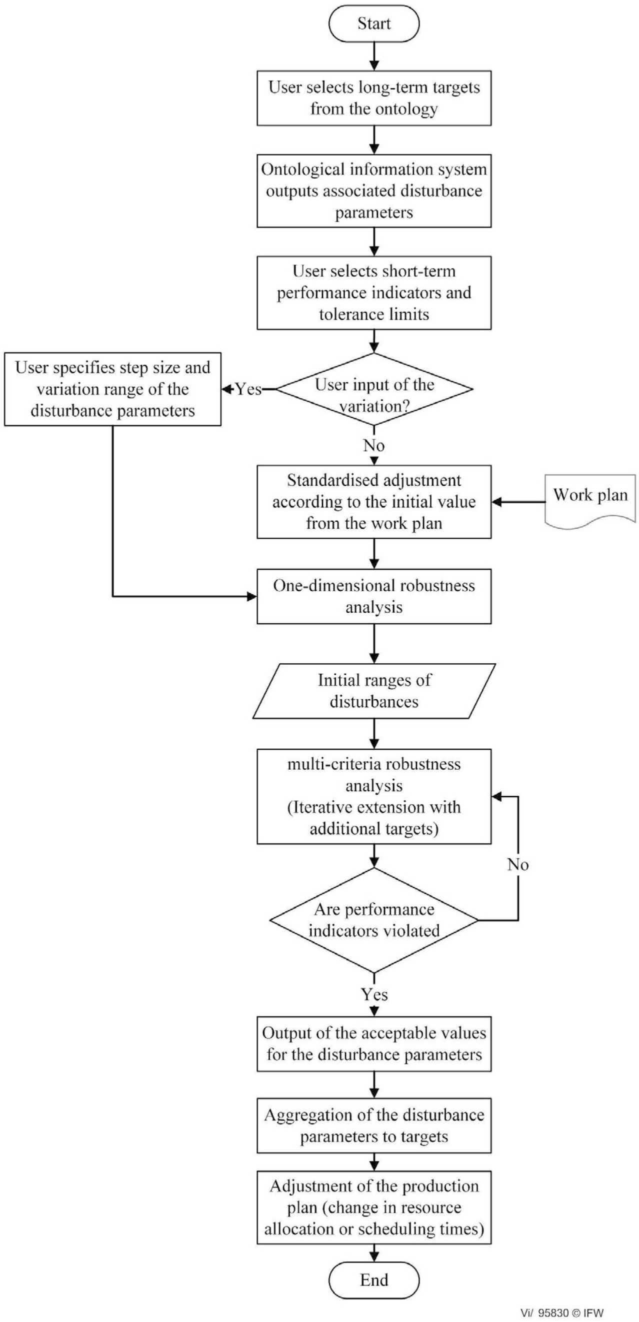

Fig. 2. Process of the multi-criteria disturbance parameters implementation

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4. Example application

To investigate the designed approach on a manufacturing system, a prototypical model of a workshop production is built. The CMSD standard is already verified for simulating any manufacturing system from standardised classes. Nevertheless, the first step of the investigation is to examine whether the characteristic properties and instances can be mapped in the ontology. The sample production system consists of four workshops (including the work preparation), a downstream assembly line, and upstream and downstream quality controls (see Fig. 3).

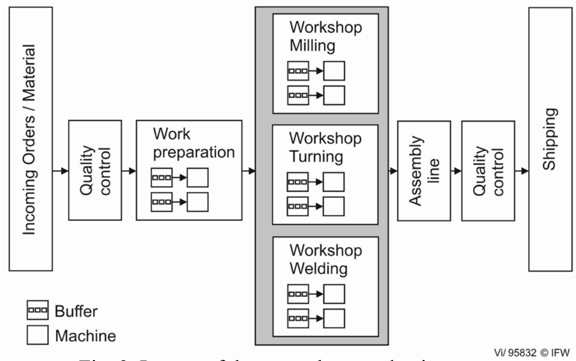

Fig. 3. Layout of the exemplary production system

Three order variants are created. The flexible structure of the system is provided by the flexible processing sequence. The orders could be allocated to the next workshop area regardless of processing status. In each of the workshops, two equal processing stations are integrated. Therefore, the following points are to be examined with regard to their representability:

- The workshop and its two equal processing stations as well as their associated buffers
- The assembly line (with one workstation)
- The quality control workstations
- The three order (workpiece) variants
- The flexible processing sequences

The processing stations of the workshop, the assembly station, and the workstations that perform the quality control are assigned to the resource information class. All components have similar functions in production and can be assigned to the potential factors as workstations (see Fig. 4). The buffers of the workshops can also be assigned to the potential factors. These can be defined as workstations which perform an operation of "buffering or sorting" and "process" workpiece for a certain time. The three sample products of the manufacturing system can be assigned as instances of the superclass of product information. The attributes product name (product ID) and work piece features are assigned to this superclass. By the expression of these attributes, the products can be clearly distinguished as instances. The workpiece features are assigned to operations from the operation information superclass. Operations are assigned the attribute operation name (operation ID) and operation dependencies (process chains). This information area can be used to map the independent machining sequence for the production system. According to the CMSD standard, all components of the model can be represented by classes in the ontology. Therefore, the information system offers the identification of all possible disturbance parameters. In a second step, it is evaluated whether the disturbance parameters assigned in the ontology can be transferred to the real instances. As an example, the technical disturbance parameters for the workstations were determined from the ontology. Fig. 4 shows the exemplary section of the ontology. The availability (failure) and the loss of performance (wear) are assigned to the workstations/ machines. The availability indicators Mean Time Between Failures (MTBF), Mean Time Between Repair (MTBR) and Mean Time To Repair (MTTR) are assigned to these disturbance parameters. For wear and performance loss, the disturbance parameter of processing time is identified by the ontology.

For the performance indicators, the output, stock and lead time are identified. Performance indicators such as the performance level or the quality level can be traced back to these indicators. That the selected performance indicators are generally valid is shown by a literature review, cited here as an example [11]. In order to evaluate the long-term targets, it is investigated whether the disturbance parameters which results from the ontology can actually be assigned to the component level of the ontology. In Fig. 4 is shown the ontological path of the long-term target efficiency, which is a sub-target of technical progress or automation. For example, the conversion of technical facilities is necessary for automation. If machines need to be retrofitted to automate processes, they are unavailable for a time. This limits the availability, which is defined as a disturbance parameter. Further it is derived how the availability is represented in the simulation. For this purpose, the allocation of the disturbance parameters to the components is defined for the information system. The upper path in Fig. 4 shows that the availability is assigned to the work system as a disturbance parameter. Machines also belong to the work stations. The information system shows that the availability can be illustrated using the MTBF, MTTR, MTBR. The selected indicators can be calculated using the time stamp of events in the simulation. Another prototypical long-term target is used to investigate the planning method. As an

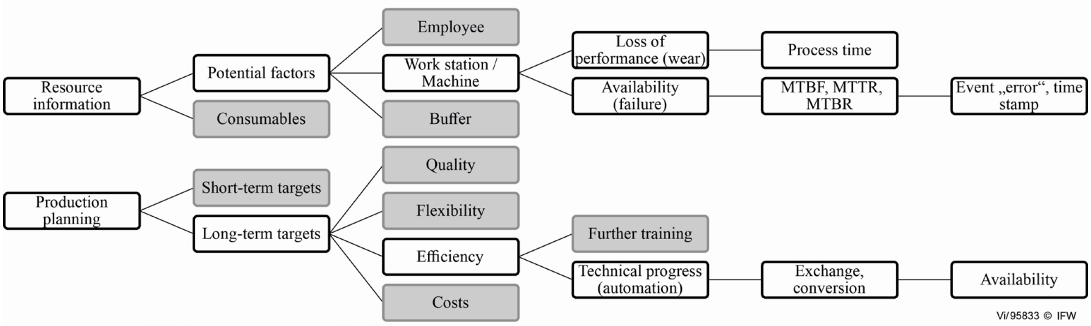

Fig. 4. Exemplary section of the ontology

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application example, the possibilities of learning at the workplace are examined. Learning at the workplace is part of the long-term target of further training. If employees are trained in the process, it leads to higher processing times. Which are selected as a disturbance parameter for the robustness analysis. Fig. 5 shows sample results of the robustness analysis. The functions show the course of the output as a function of the processing time considered for two exemplary workshops. The results show that the sample production system has only a low robustness against variations of the processing time of the work preparation (see Fig. 5 a).

Therefore, no employee without experience is assigned to this station. In comparison to the work preparation, the processing times of the other workshops can fluctuate without leaving the tolerance ranges of the short-term performance indicator. The system has a higher tolerance against disturbances at these workstations and therefore a higher robustness. It is possible to use this tolerance for the long-term target of employee qualification. In the long term, the employees improve their performance, in the short term, their deployment increases the processing time. For the transfer to planning a direct influence between performance level and processing time is assumed. How long an employee takes is determined by his or her performance. The performance represents a degree of efficiency which is given in percent. The maximum performance level is assumed to be 100%. For this reason, the planned processing time is required. With lower performance level, the processing time will increase. For the robustness analysis the material flow simulation software Plant Simulation is used. The user inputs and the determination of the personnel allocation according to the defined targets are occurred in Visual Studio with the programming language Python.

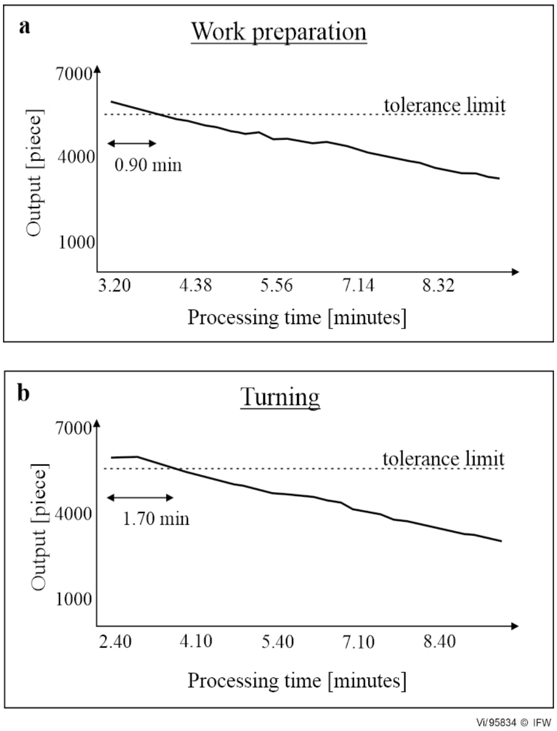

Fig. 5. Functional sequences of the output over the processing times of the workshops

5. Conclusion

The currently limited ability to integrate long-term targets into production planning and scheduling is becoming increasingly problematic due to growing system complexity and frequent replanning. In order to counteract these problems, an approach is presented which integrates a robustness analysis. This makes it possible to identify the potential scope for pursuing long-term targets. The approach integrates an ontology based on current standards, which allows the application of robustness analysis to any conceivable manufacturing system under consideration of individual company targets. The ontology includes the assignment of performance indicators to predefined manufacturing targets, as well as the assignment of disturbance parameters to the components of the manufacturing system. The ontology uses traceability to event-based data which can be recorded during production and material flow simulation. In the future, the concept of the planning method will be further developed and evaluated. The focus will no longer be on integrating as many long-term targets as possible, but on making the best possible use of the available scope for long-term target tracking. In addition to optimisation, the implemented targets should also be expanded.

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