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Concept for Material Supply in Fluid Manufacturing Systems

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Purpose: *Through increasing individualization, volatile market demands or shorter product and innovation cycles, existing assembly systems in the automotive industry reach their limits. Different approaches are designed to address the need for adaptable systems. The Fluid Manufacturing System (FLMS), which has been developed within the research campus "Active Research Environment for the Next generation of Automobiles" (ARENA2036), aims to enable flexible and dynamic material flows. However, material supply in this environment is challenging due to new degrees of freedom or volatile demands. Therefore, the purpose of this paper is to describe a concept for short-term-oriented material supply in FLMS. The concept focuses on checking and ensuring material availability.*

Methodology: *The methodology that is used to derive the concept for material supply is based on a step-by-step procedure allowing a systematic concept development using a problem-solving-oriented approach. The concept procedure includes different steps like concept initiation or selection of a solution.*

Findings: *The result of this paper outlines a concept that supports short-term-oriented material supply in FLMS. More detailed, the concept supports checking and ensuring material availability.*

Originality: *The presented concept contributes to check and ensure material availability during the operation of assembly systems under changing conditions.*

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1 Introduction

In recent years, the automotive industry has been changing in regard to various developments. Among others, existing trends are new concepts like mobility-as-a-service, connected and self-driving vehicles or electric and fuel cell drive (Winkelhake, 2021). Moreover, increasing product individualization, volatile market demands, shorter product and innovation cycles as well as new car manufacturer have led to an increasing competitive pressure (VDA, 2021). Many of these developments affect automobile production and related logistics processes. For example, producing heterogenous and customized products at an optimum operating level, using conventional rigidly linked assembly lines that once had been designed for homogenous products, is challenging (Kern, et al., 2015). Even complex assembly line balancing approaches for mixed-model assembly lines have reached their limits due to existing cycle time variations (Swist, 2014). From a logistics point of view, increasing customization, which comes along with a wide range of individual options to choose from and long opened time slots for car buyers to update the configuration of their ordered cars, have led to an increasing number of materials that are delivered from a rising number of suppliers in decreasing planning and delivery cycles (Battini, Boysen and Emde, 2013).

As a consequence, different approaches have been designed and discussed to meet the changing requirements of automobile assembly (Fries, et al., 2021; Kern, 2021). The proposed approaches are often based on the principles of changeability and use flexibly linked process modules that allow e.g. cycle-independent assembly (Foith-Förster and Bauernhansl, 2015). These production systems, however, go along with higher requirements for production and logistics planning and control. As shown in Figure 1, alternatives to assembly line production systems can be characterized by nine principles (Kern, et al., 2015).

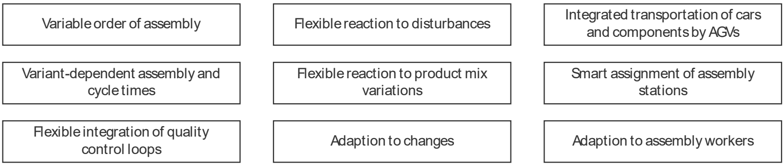

Figure 1: Principles of future assembly concepts (Kern, et al., 2015)

The FLMS that is addressed in this paper provides these principles. As one characteristic, FLMS enables flexible and dynamic material flows. This provides a basis for assembly order rescheduling, e.g. in cases of short-term deviations regarding the initial assembly schedule. Among other items, an assembly schedule contains the planned start time and end time of each job as well as all resources required for processing the assembly steps (Vieira, Hermann and Lin, 2003). As a decision-making process, scheduling deals with the allocation of specific resources to tasks within a defined time horizon (Pinedo, 2016). The process of updating an existing assembly schedule in response to disruptions or other changes is called rescheduling (Vieira, Hermann and Lin, 2003). Schedule deviations often occur during the operating phase of assembly systems, since planning data are outdated at the time of order release (Müller, 2020). Order release is defined as which orders are moved into the assembly system (Vieira, Hermann and Lin, 2003). At the same time, the moment of order release often represents the bridge between planning and control tasks.

There are various real-time events making dynamic rescheduling necessary in FLMS. They can be clustered into two categories (Ouelhadj and Petrovic, 2009):

- Resource-related events are e.g. machine breakdown, unavailability of operator, tool failures, shortage of materials or material with wrong specifications.
- Order-related events are e.g. changing order priorities, due date changes, early or late arrival, order cancellation or changes in processing time.

Basically, orders compete for the same resources and materials during rescheduling in FLMS. This is why complex logistics planning and control structures and logics are required to enable efficient material flows and dependent assembly processes. An assembly product is built by putting all its parts together. As a result of multi-part products, assembly operations can usually only be started when all the required materials are available (Schmidt, 2011). Moreover, these parts are delivered from different sources with the help of various material flows, stressing different logistical processes. As a result, ensuring material availability is challenging (Günther and Tempelmeier, 2016). Internal material supply is one of the major challenges for realizing flexibly linked assembly systems (Greschke, 2020). However, efficient assembly requires smoothly working material supply processes, since missing materials may lead to time and cost-intensive production downtimes.

To operate FLMS, new concepts are needed to accomplish one of the main logistical tasks, namely, providing the right material in the right place, at the right time, in the right quality and amount as well as at the right cost. Therefore, the purpose of this paper is to describe a concept for short-term-oriented material supply in FLMS. More detailed, the concept contributes to close an existing research gap regarding material availability checks in FLMS.

The remainder of this paper is organized as follows: Section 2 introduces FLMS. State of the art regarding material supply is described in Section 3. The concept is introduced in Section 4 and discussed in Section 5. Section 6 provides a conclusion and an outlook.

2 FLMS

The FLMS is developed within ARENA2036. As part of the University of Stuttgart, ARENA2036 is a research campus and innovation platform for cooperation between science and industry focusing on future mobility (Dittmann and Middendorf, 2019).

As an evolution of the Matrix Manufacturing System, FLMS is built up of modular and mobile process modules which are flexibly interlinked (Fries, et al., 2019). Moreover, FLMS is fully built up using Cyber-Physical Systems (CPS). CPS integrate computational and physical capabilities combined with the possibility of human-machine interaction (Baheti and Gill, 2011). As shown in Figure 2, the structure of Cyber-Physical Production Systems (CPPS) consists of the elements physical world, data acquisition, cyber world, and feedback/control structures (Thiede, Juraschek and Herrmann, 2016).

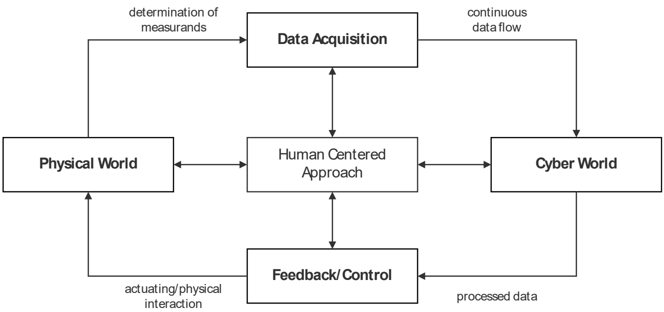

Figure 2: Structure of CPPS (Thiede, Juraschek and Herrmann, 2016)

FLMS is further based on the idea of ad-hoc resource allocation and individual process module reconfiguration (Fries, et al., 2021). Using the benefits of CPPS, process modules can be aggregated from single resources to advanced production systems (Fries, et al., 2021). This allows on-demand adjustments of capabilities and functionalities which leads to specific degrees of freedom that need to be managed within FLMS (Fries, et al., 2019; Fries, Wiendahl and Foith-Förster, 2020):

- Operation sequence specifies the sequence of work operations.
- Work distribution assigns the process modules to the production order.
- Work content defines the competencies of a specific process module.
- Layout position defines the position of production equipment on the shop floor.

These degrees of freedom make more complex planning and control logics necessary. Basically, planning processes will be shifted further into operation which means that planning and control phases increasingly overlap. Previously long term-oriented planning tasks need to be proceeded within short-term decision-making (Hagg, Noortwyck and Schulz, 2020). Moreover, this leads to changes regarding the chronology of how planning and control tasks are executed. For example, due to the high complexity and dynamic, in order to ongoing resource- and order-related events, the step of assembly order sequencing takes place after the task of order releasing (Waschneck, 2020). The uncertainty regarding the unknown production sequence directly affects just-in-sequence (JIS) delivery strategies that are often used in the automobile industry. JIS means that parts are pre-sorted by the supplier or inhouse supermarkets, so that assembly workers can access these materials just as determined by the production sequence (Battini, Boysen and Emde, 2013).

So far, resource and material availability checks have taken place within the initial process of order releasing (Schuh, Schmidt and Schürmeyer, 2014). Therefore, the developments accompanying FLMS have a major impact on the material supply process and ensuring material availability. Using decentralized methods is one possibility to deal with this complexity during the value creation processes. Dynamic scheduling is a decentralized approach that, unlike conventional scheduling, does not create long-term-oriented assembly schedules, but rather generates orders when necessary based on the information available at the moment of dispatching (Vieira, Hermann and Lin, 2003). In FLMS, assembly products are transported by using specific automated guided vehicles (AGV) for workpieces, so that fast reactions in cases of rescheduling are possible. Besides AGV for workpieces, there are also different AGV for material transport in FLMS. Regarding this, efficient scheduling functions must interact with other functions, such as ones responsible for material availability (Pinedo, 2016). Moreover, a critical point of dynamic scheduling is the high real-time requirement and the short time-horizon for material supply oriented decision-making (Zhou and Zhu, 2021). Within ARENA2036, an asset administration shell is used as a basic tool to realize data transfer and communication. Detailed descriptions of how to use an asset administration shell in FLMS and the first logistics-related implementations are already available (Bozkurt, et al., 2021; Ewert, et al., 2021). Besides several publications describing conceptual aspects of FMLS, up to now, different use cases have been implemented and tested as demonstrator on the ARENA2036 shop floor.

The above mentioned capabilities are especially relevant for FLMS, since, compared to other production systems like line based assembly systems or matrix manufacturing systems, control complexity is higher (Fries, et al., 2022). A more detailed description of FLMS and its relation to and differentiation from other production systems can be found in literature (Fries, et al., 2021). Important advantages and disadvantages of FLMS are summarized in Table 1.

Table 1: Advantages and disadvantages of FLMS (Fries, et al., 2022)

Advantages	Disadvantages
Ability to iteratively reconfigure in variable steps to the currently required product configuration	High control and scheduling complexity
Easy scalability	High costs of equipment
Changing competencies depending on process modules	Complex material flows
Continuous layout and process adaption	High effort for material supply and ensuring material availability

Heavily simplified, the production planning and control procedure for FLMS that have been designed within ARENA2036 includes three main steps (Hinrichsen, et al., 2022). First, an initial planning takes place to determine a basic production plan. Thereby, a capacity check is performed based on the individual task list of every product including factors like required technologies, personal or material. Based on the planning results, production begins and production control takes over in a second step. As long as there are no unplanned events like missing parts or machine failures, the initial defined production plan will be executed. However, if there are deviations, for example, when a process module is not available as planned or a material is missing, the production planning process is retriggered as a third step. This last step means dynamic rescheduling, as discussed previously.

The presented concept focuses on a material availability check as part of the afore-mentioned capacity check. Assembly system changes affect material flow structures and material supply processes (Blessing, 1999). Thus, the state of the art regarding material supply and approaches for ensuring material availability will be described next.

3 Material supply – state of the art

Material supply is an important design dimension of flexibly linked assembly systems (Schmitt, et al., 2017). Material supply is defined as the task of providing the required material that has already been delivered to the OEM plant, in the right amount and kind, to the right point of use as well as at the right time, to enable further processing (REFA, 1991a). Typically for automobile industry, value creation is more and more removed from the final assembly plant and shifted towards module production at suppliers (Battini, Boysen and Emde, 2013). Material supply is the connecting element between external logistic processes like procurement and the final assembly process (Nyhuis, Schmidt and Wriggers, 2008).

Several functions and parameters are used for material supply. Among others, the basic material supply functions include transport, picking, buffering, warehousing, handling (e.g. material preparation, un- and uploading) and sequencing (Esser, 1996). Material supply methods can be characterized by means of organizational and technical parameters. While the technical parameters include technical- and informational-oriented equipment, the organizational view is characterized by the following parameters (Bullinger, 1995):

- Object of material supply (identifiable by part number)
- Material demand quantity
- Material supply time as latest arrival time
- Material supply source and destination (sink as point of use)
- Material supply type (e.g. demand- and consumption-oriented strategies) and material supply form (e.g. single/set part delivery)
- Competence to trigger and execute material supply functions

Focusing on material supply in flexibly linked assembly systems, different concepts and associated technical equipment have been developed in recent years (Wehking and Popp, 2015; Hofmann, 2018). The so-called rack-concept, AGV-concept or set-concept can be mentioned as examples that have been investigated using simulation (Popp, 2018). A method for selecting the minimum-cost alternative for material supply have been proposed for these concepts (Bozkurt, Popp and Kueber, 2021).

Using the material flow flexibility offered by flexibly linked assembly systems, there might be redundant modules within the assembly layout that offer the same competencies. Hence, one weakness of flexibly linked assembly systems is the high effort for providing the same parts at different locations (Schmitt, et al., 2017). Further, new challenges for material supply arise because of the underlying systems characteristics. Particularly, uncertainty increases concerning the point of use, time of use, demand quantity as well as unknown order sequences (Ranke and Bauernhansl, 2021). This is why new control mechanisms are required (Bozkurt, Hagg and Schulz, 2020).

Further, the suitability and performance of different material supply strategies in the context of flexibly linked process modules have been evaluated and investigated (Ranke and Bauernhansl, 2021). In addition, different material supply strategies for material transport between a supermarket and matrix-structured work stations have been modeled and analyzed by using simulation (Filz, et al., 2019). The results indicate that part variance is one important factor influencing the favored material supply strategies.

Important requirements for the operational and organizational structure of material flow control systems in dynamic production environments that also apply to FLMS are (Blessing, 1999):

- Ability to change and adapt: Fast and low-effort logistical adaption to production systems changes. This may include organizational changes, increasing or decreasing the number of AGV, switch of AGV type as well as changes regarding production equipment arrangements.
- Variability of material supply control strategies: This requirement addresses the ability to switch between different control strategies and combine them without resetting the entire material flow control system. These control strategies may also differ within assembly areas.
- Data actuality and planning support mechanism: In order to deal with failures or unexpected events which may occur, the actuality of system data is important to support planning processes and short-term-oriented rescheduling. This includes e.g. information regarding inventories, material quality, AGV utilization or routes and traffic states.

A service-oriented architecture that enables a dynamic scheduling of material supply operations in line-based assembly systems has been introduced (Kousi, et al., 2016). This system is responsible for detecting the material supply requirements, triggering the material supply operations scheduler and dispatching the scheduled actions to AGV. Based on this architecture, a decision-making framework have been further developed to generate schedules for material supply tasks and assign them to available resources by using a material supply scheduler (Kousi, et al., 2019).

Moreover, first aspects of logistic planning and control in flexibly linked assembly systems are described (Kern, 2021). Central and decentral logistics areas, material supply and transport system design are described. Focusing logistics control, different material supply approaches, ways for monitoring logistical processes or fault management are discussed (Kern, 2021). However, how to ensure material availability is not considered in detail.

If parts are missing at the point of assembly, one of the following reactions is required in recent automobile assembly lines (Boysen, et al., 2015):

- If the shortfall is realized before having finally released the car, requiring the missing material for final assembly, another car can may be released into the free production slot. However, this modifies the initial planned assembly sequence and affects, for example, JIS processes, since parts need to be re-sorted.
- If the missing parts are anticipated early enough, express or emergency deliveries can be initiated and then executed by AGV.
- Another option is to continue with assembly as though nothing had happened and simply skip the missing part. When the left-out part becomes available, it needs to be retrofitted, which is time and cost intensive.
- In the worst case, the assembly line has to be stopped.

Since all these reactions cause costs and the occurrence probability of missing parts is higher in flexibly linked assembly systems with dynamic material flows than in recent assembly lines, more attention should be paid to the question of how material availability can be dynamically checked and ensured.

Checking material availability

This paper focuses on checking material availability. For multi-part products that need to be assembled, checking and ensuring material availability is a challenge that needs to be planned (Günther and Tempelmeier, 2016). Availability checks are used to clarify whether the required equipment and resources are available to perform the production as planned (Schmidt and Nyhuis, 2021). Material availability calculations are important to ensure that the required materials are delivered to the point of assembly in due time (REFA, 1991b). In literature, a distinction is made between static and dynamic availability check procedures (Scheer, 1998).

Static availability checks take place before order release, where it is necessary that all resources that are needed to complete the assembly step are physically available at the time of carrying out the availability check (Scheer, 1998). After the materials are assigned to orders, they are reserved to ensure that they are not allocated more than once. A lot of time might pass between order release and real assembly start, which means the in-time availability of the required material at the point of assembly is not ensured. In contrast to the static availability check, dynamic checks do not require the physical availability of materials until the beginning of assembly processing (Schmidt and Nyhuis, 2021). For example, simulation can be used to forecast order progress and material availability within dynamic availability checks (Scheer, 1998).

So far, little attention has been paid to material availability checks in dynamic production and logistics environments. Because of the ad-hoc allocation of resources that enable shorter system adaption times, however, the time to perform logistic tasks is reduced in FLMS. Moreover, dynamically changing process module positions over time challenge material supply in general and ensuring material availability in particular. In FLMS, the frequent occurrence of order- and resource-based events will make dynamic rescheduling necessary more often. Therefore, a new concept needs to be developed that takes these aspects into consideration and helps to close the described research gap concerning material availability checks in FLMS.

4 Concept for Material Supply in FLMS

4.1 Methodology and procedure

As shown in Figure 3, the concept involves four different procedural steps: concept initiation, searching for objective and task deduction, searching for solution as well as selecting a solution.

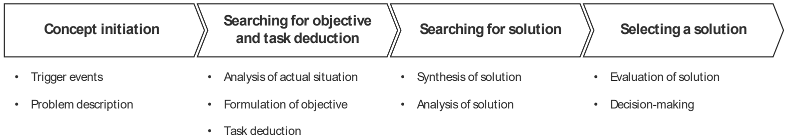

Figure 3: Concept structure and procedure

The methodology that is used to derive the concept for material supply in FLMS is based on a step-by-step procedure allowing a systematic concept development using a problem-solving-oriented approach. The four-step structure of the proposed concept is based on a problem-solving process that can be applied to a wide range of technical products and systems design (VDI, 2019a). In this case, the procedure is adapted to check material availability in the context of material supply and the concept supports decision-making regarding short-term-oriented material supply. Thus, the concept focuses on material availability checks as part of the entire material supply system in FLMS. As result, the concept contributes to ensure material availability during the operation of assembly systems under changing conditions. After the concept has been carried out and, depending on the final decision-making result, the execution of material supply functions might take place on shop floor level. These subsequent steps, which are not part of the concept described in this paper, include e.g. explicit load-vehicle assignment, empty vehicle balancing or routing (Schmidt, et al., 2020).

Before the concept is described more detailed in Section 4.3, important aspects regarding the underlying material and information flow, as well as how the concept will be embedded in the surrounding system, will be outlined.

4.2 Material and Information flow

It is widely known that synchronized material and information flows are important for successfully material supply. Moreover, well-balanced and synchronized logistic and production processes are also essential to operate FLMS. Manufacturing Execution Systems (MES) are important to manage production and logistic tasks, since they ensure process transparency or provide an up-to-date mapping of material and information flows (Kletti, 2015). As a centrally organized and a monolithic software application, currently MES are often integrated between the enterprise control level and manufacturing level within the control levels of a company. (VDI, 2016; 2021). However, in order to accommodate the increasing digitalization and the new requirements coming along, e.g. with production systems like FLMS, traditional MES architecture will change. In future, the monolithically structured MES will be separated into individual and independent applications that will be interconnected and communicate with each other in a decentralized manner during the value creation process (VDI, 2021).

Therefore, the concept presented here can be realized and implemented as a decentralized decision-making module that is able to collect and share all necessary data as well as interact with other system elements. The extensive information access in FLMS permits the use of local as well as global information for decision-making. While global information represents overall system knowledge, local information is only available locally (e.g. specific information of a load carrier that are not relevant for the overall system) (Schmidt, et al., 2020). As mentioned in section 2, the asset administration shell is used for coordinating material and information flows within FLMS.

4.3 Specifying the concept structure

4.3.1 Concept initiation

The aim of this step is to identify events that trigger the concept and to describe the basic problem statement by which the concept is initiated. Figure 4 illustrates the concept initiation procedure.

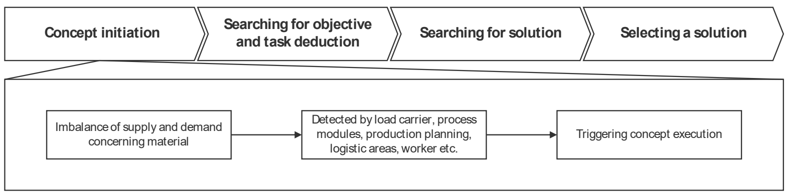

Figure 4: Concept initiation

Trigger events and problem description

In FLMS, changing operation sequences, work distribution, work content and process module arrangements may lead to shifting points of assembly where materials will be required. The problem to be solved occurs if there is a deviation between the quantity of material available at a specific point (e.g. point of assembly) and the material required. Basically, the problem is that the required material is not available where it is needed. Thus, there is an imbalance of supply and demand regarding material.

Because of the fast adaption potential of FLMS, it is expected that this problem will arise more frequently in FLMS than in other production systems. The wide availability of information supports the early detection of resource- and order-related events (e.g. missing or damaged materials), so that material-required actions can be initiated without loss of time. For example, if material that is transported using a CPS-based load carrier is damaged during transportation, these quality issues can be detected by the load carrier itself through implemented sensors and further steps for material replacement can be initiated (Bozkurt, et al., 2021). If the damaged material cannot be replaced or repaired in the remaining time, however, material availability cannot be ensured for this part. Different system entities are able to recognize such deviations between the material needed and actual state availability. Beside load carries, other entities respectively CPS can act as problem-identifiers and concept-initiators, e.g. production and control processes, AGV, worker, process modules, logistics or warehousing areas. Once the problem occurs and has been identified, the next steps can be triggered by these system entities to check if the problem can be solved. Hence, concept execution is usually triggered by events (e.g. unplanned events that require rescheduling).

4.3.2 Search for objective and task deduction

The next concept step deals with searching for an objective. The aim is to conduct a detailed analysis by providing additional information about the actual and target system state. Moreover, the final task is developed within this concept part. Therefore, searching for an objective procedure consists of three parts: analysis of actual situation, formulation of objective and final task deduction.

Analysis of actual situation

The analysis of actual situation aims to get an overview of the current situation. Therefore, it is necessary to take all important factors influencing the material supply system into account. For this purpose, the material supply parameters described in Section 3 are used to get an overview of the actual situation. The result of this step is a detailed analysis of the actual shop floor situation in terms of material supply relevant parameters.

Formulation of objective

Within the next step, the objective formulation takes place. Describing the desired final state makes it easier to search for possible solution alternatives afterwards. The objective must represent the final state that should be achieved after carrying out all the concept steps. Again, the material supply parameters are used to describe the objective situation. In contrast to the previous actual state description, however, the objective is formulated now. This guarantees that material supply parameters for describing the actual state as well as the objective situation match. As result, there is a clear objective formulation.

Task deduction

This step aims to deduce the final task by using the actual system analysis and the objective formulation. The deduction of the task focuses on the question which material supply activities are necessary to transfer the actual system state to the defined objective state (VDI, 2019b).

For this, a deviation analysis is performed to identify discrepancies between the material supply parameters representing the actual situation and those mapping the objective state. To identify the deviations between the target and actual states, the material supply parameters are systematically compared step-by-step. Thereby, all tasks that are necessary to transfer current material supply state to the objective state are identified.

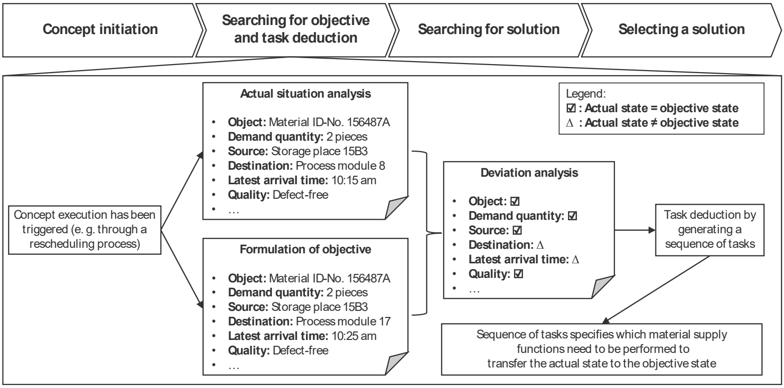

Figure 5: Searching for objective and task deduction

As result of the deviation analysis, a sequence of tasks can be generated (Kousi, et al., 2016). Based on this task sequence, it is known which material supply functions need to be executed to overcome the gap between material demand and material availability. In other words, the sequence of tasks specifies which material supply functions need to be performed to transfer the actual state to the objective state. Exemplarily, the described concept steps are summarized in Figure 5. However, the fact that the actual as well as target states can change dynamically over time in FLMS needs to be considered. As a consequence, several iterations can be necessary and explicit stopping criteria need to be defined.

4.3.3 Search for solutions

Based on the generated task sequence, solution options can be worked out to fulfill the defined task. Therefore, the concept step for searching for a solution consists of the synthesis of solutions and a subsequent solution analysis.

Synthesis of solution

The synthesis of solution aims to identify alternative solution options to execute the sequence of tasks. As a result, a collection of all possible solution options is generated to transfer the actual state to the objective state. These options can be stored, e.g. in a matrix table, for further processing. By synthesizing solutions, different conditions and limitations can be considered to border the number of possible solutions. This reduces the planning effort. Considering specific weight and size rules or the availability of logistic areas are examples for such limitations. Moreover, the available material supply equipment and existing material supply strategies (e.g. for transporting or warehousing) influence the number of possible solutions. For example, if the sequence of tasks contains the task transport and if there are different transportations alternatives available (e.g. AGV or forklifts), there might be more than one solution for the execution of the transportation task. As result of solution synthesizing, there is a collection that contains all possible options for executing the sequence of tasks. One of these option alternatives should be that material availability cannot be realized.

Analysis of solution

Within the next step, the generated collection with possible solution options needs to be analyzed in terms of their properties. The solution alternatives are investigated regarding the resulting consequence if this option is chosen. Therefore, different material supply relevant dimensions can be applied. These dimensions may include cost-, capacity- or time-relevant aspects that are linked to the logistical target system (Droste, 2013). For example, focusing on the time dimension, the solutions options are analyzed regarding the resulting consequences in terms of material supply synchronization or timeliness (Nickel, 2008). The resulting consequences can emerge in different environmental states due to existing system uncertainties, so that different occurrence probabilities can be considered by analyzing the consequences. In addition to the afore-mentioned dimensions, other dimensions, like logistical process sustainability or human ergonomic aspects (Droste, 2013), can be added, since the structure is modular. Figure 6 illustrates the concept steps for solution synthesis and analysis.

Before evaluating possible solution options in the next step, the resulting consequence of every option is analyzed and added to the collection of possible solution options. The result is a collection of all possible alternative solutions and the anticipated consequences that occur if the respective solution option is realized.

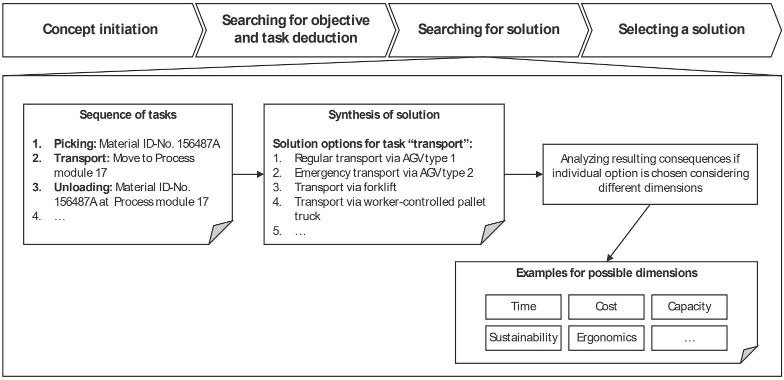

Figure 6: Searching for solution

4.3.4 Selection of solution

The last step of the concept procedure deals with the solution selection and consists of the evaluation and decision-making processes. The aim is to choose the best suitable solution option.

Evaluation of solution

As a basis for final decision-making, the consequences of every solution option need to be evaluated. Therefore, the comparability of the dimensions values and properties must be insured. This is challenging in order to eliminate inhomogeneous value characteristics. Further investigations are necessary to identify suitable methods that allow interpretable evaluation of solution options (e.g. using non-dimensional approaches).

Decision-making

After the evaluation process, the fittest solution option needs to be chosen. However, this option might change over time and depends on individual preferences. Moreover, individual entity goals in FLMS are often conflicting and mutual dependencies exist. In one situation, it might benefit the overall system performance if the solution with lowest material supply cost is chosen. Whereas, in another situation, it might be favorable if material supply processes temporarily cause higher costs to enable the assembly of a highly prioritized product.

In cases of short-term rescheduling processes, it is also possible, however, that material availability cannot be ensured and cost intensive production downtimes arise. This can happen if the remaining time for material supply is not sufficient by using the existing material supply equipment. Then, the production rescheduling process is performed again to check other options for processing the next assembly step.

Consequently, a dynamically adjustable decision rule is required for decision-making. A decision rule is built up by a preference function and a optimization criteria for the preference value (Laux, Gillenkirch and Schenk-Mathes, 2018). Based on this, the evaluated solution options are prioritized in a first step, and then the option with the highest priority is chosen. The full details and final design of such an adaptable decision rule for FLMS need to be further developed. One option might be a decentral-oriented decision rule using dynamic negotiation approaches for dialogues between the system entities that are involved in the material supply process.

The result of the decision-making step indicates whether the material availability can be realized or not. If material availability can be realized, the next steps are initiated (see Figure 7). For example, feedback is sent to the capacity check triggered by rescheduling processes, whereupon process modules can be reserved or required material reservations are initiated. The final execution of the material supply processes and the continuous monitoring of these processes is not part of the presented concept. If material availability cannot be realized, a dismissal is sent to the initiator of the initial request by using feedback loops. As a result, the proposed concept contributes to logistics interacting on par with assembly in FLMS.

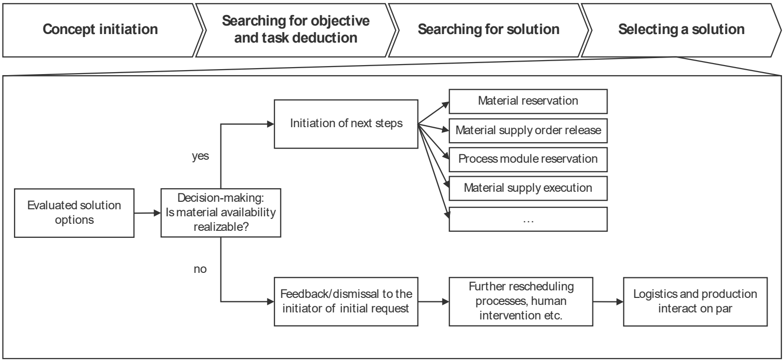

Figure 7: Selecting a solution

5 Discussion

In the last section, a concept that supports short-term-oriented material supply in FLMS have been presented. More precisely, the concept investigates whether material availability can be realized or not. One benefit of the described concept is that it supports using the degrees of freedom that accompany with FLMS. Moreover, it contributes to reduce logistics-related traffic volume and the total quantities of transports. This is possible through an early check of material availability and an effort estimation for the required material supply processes to enable material availability. Additionally, the concept supports the material flow control system requirements described in Section 3 in FLMS environments. Particularly significant are the ability to change and adapt, the variability of material supply strategies and planning support mechanism through data actuality.

However, there are challenges and limitations regarding the presented concept that need to be addressed in future. The required estimation and anticipation of future environmental states is a weakness of the concept. Moreover, missing cycle times complicate material availability calculations. A closer look is necessary to investigate the utility of the proposed concept regarding the material spectrum to be supplied. For example, to clarify how to handle high or low material variance. Under specific production and logistics conditions, it might be beneficial to use a pre-sorted material set that is carried along with the product to be assembled. These conditions have to be analyzed in more detail. Further, logistics and assembly processes are characterized by inhomogeneous responsiveness times for changes and adaptions in FLMS. These aspects should be implemented more explicitly as part of decision-making within the introduced concept. Moreover, solution for other key challenges like technical-, algorithmic- or systems engineering-related concept aspects need to be developed in future.

6 Conclusion and outlook

This paper deals with material supply in FLMS. The result outlines a concept that supports short-term-oriented material supply. More specifically, the concept supports the evaluation of whether the material availability can be realized within a short-term-oriented time horizon. Therefore, the concept involves the following main procedural steps: concept initiation, searching for an objective and task deduction, searching for a solution as well as selecting a solution. These procedural steps have been worked out and described in more detail.

The presented work has implications for research and practice, since it complements related approaches and existing literature for material supply. Moreover, the introduced concept is an important module for efficient material supply in FMLS and it extends logistically-oriented control and planning methodologies for flexibly linked assembly systems.

Further research is needed for a deeper development of the concept and to reduce existing limitations that have been mentioned in Section 5. Efficient mechanisms for avoiding permanent rescheduling processes must be implemented and stopping criteria need to be defined. For example, how emerging deadlocks could be handled, e.g. by rule-based human intervention, should be investigated. The presented decision-making environment is characterized by heterogenous properties like conflicting goals and mutual dependencies that need to be balanced. These points need to be worked out in more detail and can be investigated using simulation.

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