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Digitalisation Of Process Knowledge And Automated Decision Making In Production Steering- Recent Advances Of The Maximal Network Plan

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Abstract

Assembly processes of large structures like aircrafts, busses, railway carriages, and others typically consist of long chains of sequential and parallel production steps. Therefore, network plans are used in PPS systems to describe dependencies and calculate schedules. The limitation of this concept lies in the fact that common network plans are only able to hold a single valid sequence. Known and reasonable alternative sequences are discarded because they cannot be stored in a network plan. In the case of disturbances a manual ad hoc replanning must take place, which is time consuming and inefficient. The aim of the maximal network plan (MNP) is to overcome this limitation. It can hold prioritised alternative procedures. If the regular sequence is not feasible, another sequence with a lower priority is being proposed automatically. The data structure is based on the adjacency matrix, which contains nodes and weighted edges, and allows numerical evaluation and real-time decision-making. This can be used in conjunction with mobile computing devices instead of paper-based documents to achieve a very dynamic but consistent planning system. Current developments include the ability to contain logical XOR decisions in the MNP to incorporate process variants, understood in this context as redundant technological chains. Whereas so far only the order of a fixed contingent of process steps could be alternated, now subsections of the network plan can be varied if more than one technological process chain is available to manufacture a product. Another recent advance is aimed at the decentralised collection of additional alternatives on the shopfloor. A forecast of process steps is provided to the user. If the local situation on the shop floor allows another production step to be performed then those projected by the system, the worker can make a proposal himself. This can either be rejected or accepted by the planner and kept as a permanent alternative sequence. The aim is to continuously develop the knowledge contained in the MNP and to incorporate the experience of the workers into the planning system.

Keywords

Digitalisation; Production planning and scheduling; Knowledge management; Automated decision making; Industry 5.0

1. Introduction

Already under the Industry 4.0 paradigm some authors pointed out the significance of humans in production. For example, Romero et al. proposed in [1] an "Operator 4.0" typology and defined a set of characteristic roles of humans in the context of interaction with machines and intelligent systems in Industry 4.0. This included the type of the "Smarter Operator" as well as the "Analytical Operator". Both refer in different perspectives to the support of the workers decisions and actions by computer systems. Consequently, one of the several aims of Industry 5.0 is to empower workers through the use of digital devices, endorsing a human-

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centric approach to technology [2]. One of the enabling technologies to this is the ability to respond to new or unexpected conditions without human support, as lined out in [3].

This works deals with the development of methods that enable a dynamic production planning, especially for the use in complex manual assembly processes. The focus is on the digitalisation of process knowledge and, based on this, automated decision making especially in the context of disruptions of the standard process. Process knowledge is stored in a database and can be numerically evaluated to make the best decision for the actual situation. Users have their specific professional roles and interact with the system accordingly. An overview of the structure is shown in Figure 1.

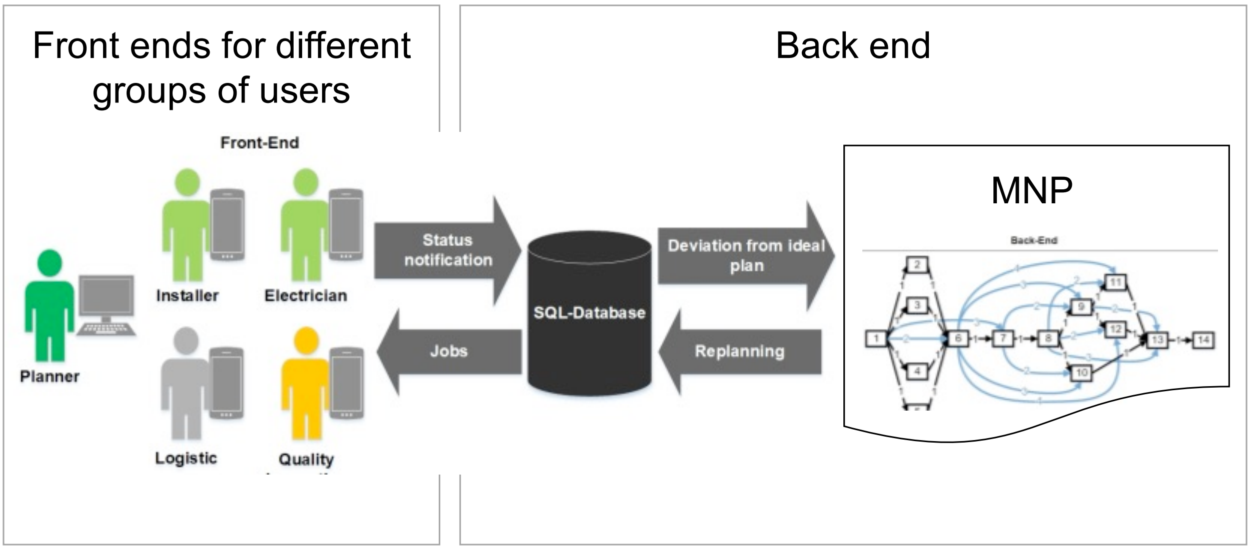

Figure 1: Structure of the MNP planning system

The methodological key to this is the progress made in the theory of network plans in order to extend their capabilities. Previous work has focused on the ability to describe prioritised alternative process sequences and the development and implementation of exemplary applications. The term Maximal Network Plan (MNP) was coined for this, referring to the Maximal Work Plan, which contains verbal and organisational information for the manufacture of a product in its configuration variants. The fundamentals of the MNP are outlined in Chapter 2 with references to the relevant literature. Ongoing work deals with the introduction of logical XOR decisions in the MNP to enable the description of redundant process variants. This is described in Chapter 3. Following the spirit of Industry 5.0 to focus on humans in production and their knowledge and skills, a novel human centred extension of the MNP is explained in Chapter 4.

2. State of the art

Production planning and scheduling systems (PPS) use hierarchical product models, such as the product breakdown structure, or directed graphs such as network plans, to steer complex manufacturing processes. Especially the assembly and installation of equipment into large structures, such as aircraft, trucks, buses, railway wagons and others, can be described very efficiently in network plans. They are capable of describing long sequential and parallel chains of tasks, as it is typical for assembly operations that are subject to a given order of task execution from a technical perspective.

Another field of work in PPS is the scheduling of large numbers of independent machining jobs. The principle of the so-called job shop scheduling problem is that a specific order of the jobs is not technically required and thus can be varied to achieve high throughput and utilisation and short lead times for the machine tools used. Research deals with strategies to find the optimal order of jobs, based on arrival time, setup time and processing time, as described for example in [4][5]. This application is not considered further in the following chapters, as the focus is on the execution of complex sequences.

2.1 Graph-based process planning methods with the ability to include alternatives

In 1967, Crowston and Thompson [6] proposed the Decision Critical Path Method (Decision CPM) as a project management tool to determine the optimum of a process in terms of costs. It is able to describe different procedures of performing a particular project and determine the individual costs of each option. In the planning and execution phases, decisions can be made which are represented by specific nodes. Homem de Mello and Sanderson [7] describe all variants of manufacturing steps for a given product using AND/OR graphs, but without any weighting. Therefore, all alternative procedures have the same priority. Rochow et al. developed a precedence graph based on the product breakdown structure. The graph contains all technical constraints between its elements. The precedence graph is transferred via an adjacency matrix to an algorithm that computes all possible process sequences. No distinction is made between the various alternative sequences, so all solutions are understood as equally feasible and efficient [8]. Petri nets are used by Zha et al. to store assembly sequences including process data such as assembly time. The sequences are generated from a CAD model of the assembly. However, the demonstrated example consists of only 4 parts [9]. Gunji et al. propose the simulated annealing method to generate all possible assembly sequences for a given assembly of 9 parts, and design for assembly principles are applied to eliminate infeasible solutions [10].

All of the above methods are mainly suitable for small problems due to the high complexity of the resulting graphs, caused by the aim to describe all theoretically possible variants. Furthermore, none of them includes weighting in terms of a prioritisation or discusses a use in the context of short-term production troubleshooting.

2.2 Network plans in production planning

A network plan is a directed graph that can also be described by an adjacency matrix of size *n x n*, where *n*, is the number of nodes in the graph. Every node represents a self-contained work step. Each edge of the graph is stored in the corresponding field of the top triangular matrix. All edges are of equal rank and therefore "*1*" is the particular entry in the matrix. The main diagonal consists of zeros because the nodes of the process cannot interact with themselves. Furthermore, there are no backwards directed edges and therefore also only zeros in the lower triangular matrix. Figure 2 shows a simple network plan and the corresponding adjacency matrix.

	V1	V2	V3	V4	V5	V6	V7
V1	0	1	0	0	0	0	0
V2	0	0	1	1	0	0	0
V3	0	0	0	0	0	1	0
V4	0	0	0	0	1	0	0
V5	0	0	0	0	0	1	0
V6	0	0	0	0	0	0	1
V7	0	0	0	0	0	0	0

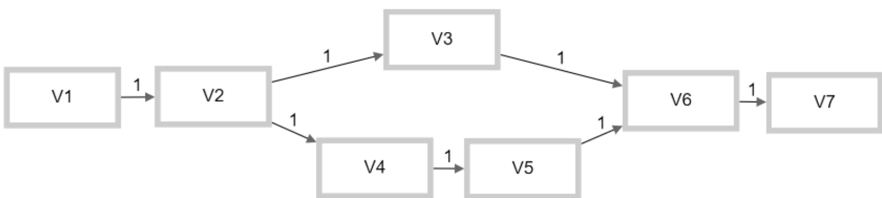

Figure 2: Adjacency matrix and network plan for a simple planning problem

An advantage of this concept is the duality of adjacency matrix and graph. The graph is easily understood by humans and can be used to describe and visualise the planning problem. The adjacency matrix, on the other hand, can be used for numerical calculations to evaluate for example the order of process steps, cycle times, schedules and resource demand over time.

In industry, graphs with several hundred nodes are used to describe complex assemblies. They can be split into subsections to share the responsibility between different planners and manufacturing departments. They can also be hierarchical, with higher level nodes representing key assembly steps that contain detailed plans for specific inherent procedures. The demand for several different resources is taken into account for each node, such as technical qualification of the worker, availability of materials, availability of space on the assembly site as well as the logistical staging area and further more [11].

2.3 The concept of the maximal network plan

The aim of the Maximal Network Plan is to overcome the limitation of conventional network plans, which contain only one valid sequence. It was introduced in [12]. The MNP is able to describe prioritised alternative procedures based on additional edges with a lower priority compared to the main process. In the following, these edges are referred to as alternative edges. The set of nodes representing the different work steps is identical. Figure 3 shows the example network plan including two additional alternative edges. If node V2 cannot be started for some reason, node V3 can be executed, assuming an acceptable amount of extra work caused by the unconventional sequence.

	V1	V2	V3	V4	V5	V6	V7
V1	0	1	2	0	0	0	0
V2	0	0	1	1	0	3	0
V3	0	0	0	0	0	1	0
V4	0	0	0	0	1	0	0
V5	0	0	0	0	0	1	0
V6	0	0	0	0	0	0	1
V7	0	0	0	0	0	0	0

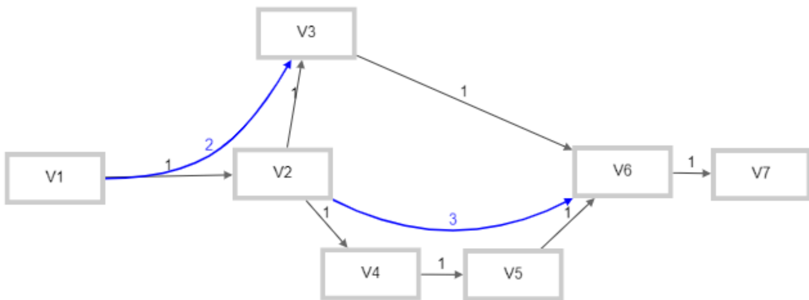

Figure 3: Adjacency matrix and network plan for a simple planning problem including alternative edges

The edge weight of the alternative edges is set in relation to the expected additional effort. It can be understood as a penalty; the higher it is the less desirable is the related path because of its deviation from the standard process. Still, it is more desirable than a complete halt in the overall progress of the work. An analytical approach is to set the penalty corresponding to the maximum number of skipped nodes in any parallel path regarding the growing deviation from the standard process. In practice, the value can be chosen freely as long as it is greater than *1*, which represents a standard process.

The degree of freedom resulting from this approach needs to be managed in different ways. The main paradigm is to stay as close as possible to the standard process to limit any additional effort. Therefore, there must be rules that clarify the order of execution of nodes from different categories. Previously blocked and now available nodes as well as any indirectly blocked successors of them, for example, must be performed before other due nodes are started. Furthermore, an additional extension is the introduction of backwards facing edges to define preconditions, which must be fulfilled before an alternative edge becomes effective. Figure 4 shows an example with a precondition pointing from node V6 to node V4, drawn in yellow with edge weight *1*.

	V1	V2	V3	V4	V5	V6	V7
V1	0	1	2	0	0	0	0
V2	0	0	1	1	0	3	0
V3	0	0	0	0	0	1	0
V4	0	0	0	0	1	0	0
V5	0	0	0	0	0	1	0
V6	0	0	0	1	0	0	1
V7	0	0	0	0	0	0	0

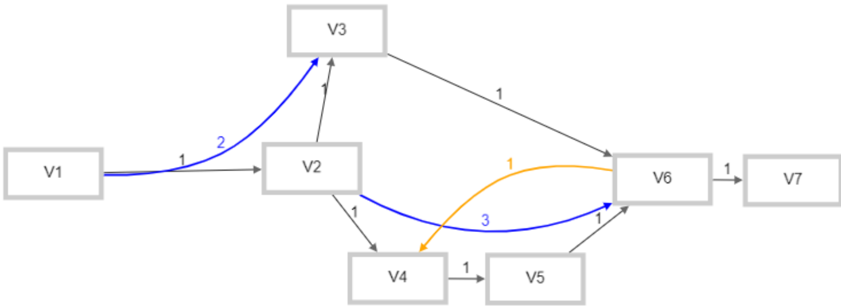

Figure 4: Adjacency matrix and network plan for a simple planning problem including a precondition

There is an alternative edge pointing from V2 to V6 with the edge weight *3*. This edge bypasses V3, but also the sequence of V4 and V5. The precondition determines that V6 can only be started if V4 has been completed to a certain degree. The criteria must be defined by the planner beforehand and can be checked manually or automatically. An edge weight of *2* can also be set for a precondition, specifying that the node to which the edge points must be fully completed.

Another feature of the MNP is the storage of status values in the main diagonal. The condition of every node is specified at any time as blocked (*-2*), repaired (*-1*), available (*0*), in progress (*1*), or completed (*2*). This is necessary in order to calculate the priority list of nodes due at any time during the execution of the overall plan.

Unlike most of the concepts mentioned in Section 2.1, the aim of the MNP is not to include all possible sequences, but a standard process and a selection of acceptable alternatives. The corresponding procedure for prioritising available nodes and further rules for defining preconditions are described in detail in [13] and [14]. Practical applications and use cases of the MNP are outlined in [15] and [16].

3. XOR decisions

Working through the MNP so far means that all nodes have to be executed. Every node represents a unique manufacturing step that is needed to finalise the complete product. Only the sequence can be altered if necessary by following edges with a different priority. To enhance the field of application in terms of automated decision making in complex assembly sequences, the possibility to use different process variants has been developed and exemplary implemented, based on EXCLUSIVE OR (XOR) decisions.

3.1 Introduction

XOR is known from Boolean Algebra and is widely used in computer science and engineering applications. Typical use cases in this context are:

- Different technologies are available to achieve a given manufacturing task, e.g. an automated facility and a manual workplace can perform similar operations.
- The product includes alternative configurations that require other manufacturing steps.

Consequently, the process variants are redundant. This leads in comparison to the so far existing MNP methodology to the novelty that nodes are not executed if they are in a deselected path.

3.2 Methodology

An XOR path in an MNP starts with a decision node. A decision node is a regular process step with two or more successors. It is referred to in the following as XOR start node. When the task specified in the XOR start node is completed, a decision must be made for one of the following optional nodes. This must be implemented in the corresponding scheduling software. Both automated and manual decisions are possible.

For example, if the configuration of the manufactured product or the availability of a preferred resource can be determined automatically, this information can be used to make the appropriate decision. In other scenarios, depending on the use case and the implementation, manual decisions need to be made on the shop floor or in the administration. Based on this decision, only one successor is selected, all others and their subsequent paths are dropped.

The edge weight for standard edges in the MNP is *1*, as discussed in Section 2. For XOR decisions, the edge weight for each successor of a decision node is defined as *1* divided by the number of variants available. Thus, the weight is greater than zero and less than or equal to *1/2*, since there is a minimum of *2* for the number of available variants. There is no limit to the number of variants. The start of XOR paths can therefore be clearly identified visually and numerically by the edge weight.

The different XOR paths always meet at the XOR end node to continue with the main production path. Visually, the XOR end node can be easily identified in the graph as the node where the split paths meet again. Numerically, the XOR end node can be identified by an algorithm that searches the branches for the next node that has sequences leading backwards through all variants to the XOR start node. Each XOR path can contain further sub-structures, splits and other XOR decisions. To find the XOR end node, each new split within an XOR path is reduced to its start and end nodes. This is done recursively for each sub-split until each path is reduced to a sequential path. If these sequential paths contain the same element, the last node of the XOR structure is found. Otherwise, the search depth must be increased until the XOR end is identified.

Figure 5 shows a simple example of a MNP including an XOR path. V2 is the XOR start node. There are two variants of the process. One variant includes node V3. The other variant includes two manufacturing steps consisting of nodes V4 and V5. The edges leading from the XOR start node to the next node consequently have edge weight *1/2*. V6 is the XOR end node.

	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**
V1	0	1	0	0	0	0	0
V2	0	0	1/2	1/2	0	0	0
V3	0	0	0	0	0	1	0
V4	0	0	0	0	1	0	0
V5	0	0	0	0	0	1	0
V6	0	0	0	0	0	0	1
V7	0	0	0	0	0	0	0

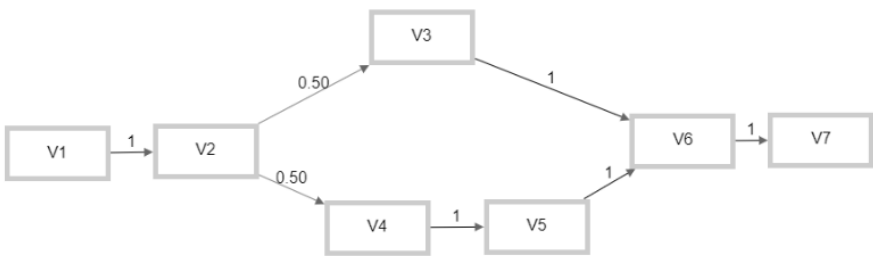

Figure 5: Example for a MNP including a XOR path with adjacency matrix (left) and graph (right)

3.3 Additional rules

A set of rules is necessary to avoid logical mistakes when using XOR decisions within a common MNP. Since not every path of the plan is executed, the following rules apply to the specification of alternative edges:

- Alternative edges must not lead into XOR paths from outside the XOR structure.
- Alternative edges must not link different XOR paths.
- Alternative edges to nodes outside the XOR structure are permissible.
- Alternative edges within the same XOR path are permissible.

Alternative edges from outside of an XOR structure must not lead into XOR paths, because the decision for one of these XOR paths may be not known at the moment the disturbance occurs. Otherwise, there could be an alternative edge leading to a process step in an XOR path that later on will not be selected and thus not be executed.

On the other hand, a disturbed step within an XOR path might be circumvented by an alternative process step later in the XOR sequence or outside of the XOR structure. The decision for the respective XOR path has already been taken so no further impact on the MNP needs to be considered. When the disturbed step is repaired, the process sequence is continued from that node on. Still, it is not permitted to have any alternative edges linking parallel XOR structures as some of them have already been excluded by the previous decision. Within an XOR path parallel processes and XOR decisions are allowed. Preconditions must be within the same XOR path or completely outside of the XOR structure. No precondition relations to parallel XOR paths are allowed.

4. Human centred extension

In all ongoing developments of the MNP the automation of decision making has been put in the center of attention, thus leading to a higher efficiency in the execution of complex working tasks but also to a lower level of participation of the working staff. It has been learned from field studies and user discussions that the recent concept of the MNP still lacks the ability to handle reasonable but undocumented alternative process sequences.

Currently the underlying concept of data creation relies on the planner, whose experience and knowledge are documented in the MNP. The more complex the assembly task is, the more likely is the existence of further alternative sequences of execution that become visible to the worker on the working ground. In addition, situations can arise that have not been taken into account when the MNP was designed. Both situations are addressed in a further extension of the MNP methodology and implementation.

In the MNP methodology a forecast of working tasks that may lie in the near future is provided. The horizon of tasks in the forecast is flexible and can be determined based on the general requirements of the use case. Possible options are:

- nodes that lie within a specific number of edges in the due sequences;
- nodes that lie within a range of execution time;
- nodes that require a specific qualification or resource that might be available.

These rules are used to generate an automatic proposal. Additional working tasks are not in the logical chain of task execution in the network plan and therefore they are not in the cycle of an automatic proposal. The worker now can propose the execution of another task instead of those that are in the logical sequence of the MNP by picking one task out of the provided forecast. Depending on the impact of the decision, different levels of approval are possible:

1) No approval needed, the proposed task can be executed straight away.
2) An automatic approval is given based on parameters that can be checked by an algorithm.
3) A manual approval is given by the responsible planner.

Option 1) is feasible in case the task is completely independent from other tasks. A practical example is the installation of fixation brackets for equipment installation in a large structure like a bus, truck or aircraft. The installation might be due at a later assembly stage but it does not cause additional effort if it is executed earlier.

Option 2) is comparable to 1 but takes into account the availability of a limited resource, like certain equipment or material. This can be determined automatically if the inventory is tracked in an automatic database. The approval can be given automatically.

Option 3) requires the expertise of a planner to ensure that all boundary conditions are fulfilled and no interference with other tasks can occur.

Specific questions are:

- Will other tasks be disturbed or blocked?
- Is the required material available?
- Is the execution of the task feasible?

To secure the high dynamic of the planning system, this approval should be given in a short period of time, which will require a responsible planner to be available. Options 1 and 2 require a predefinition in the planning phase, which has not been investigated and specified yet.

The user proposed sequence implies that there can be an additional alternative edge between the predecessor and the proposed successor. The responsible planner can store the additional information in the MNP as new additional alternative edge. This means that in future cycles of execution of the network plan the now manually proposed order of tasks can be proposed automatically. It is important to note that these edges can only have an edge weight higher than *1*. If they should become standard processes, a replanning of the relevant section of the MNP becomes necessary.

As mentioned earlier, the bidirectional communication of the worker with the planning system is based on mobile computing devices. So far, the front end for the working staff is used to display the actual task and its specific attributes, such as task descriptions, technical parameters, drawings, and even graphics and 3D models. Now it becomes a means of extended communication and interaction for the working staff. Their proposals are systematically taken into account and will be documented as part of the MNP.

The human centred extension of the MNP was implemented in the software MNPplan. Figure 6 shows the frontend from the workers perspective. The software proposes work steps in the categories: *Working*, *Regular*, *Alternative* and *Others* (see Figure 6).

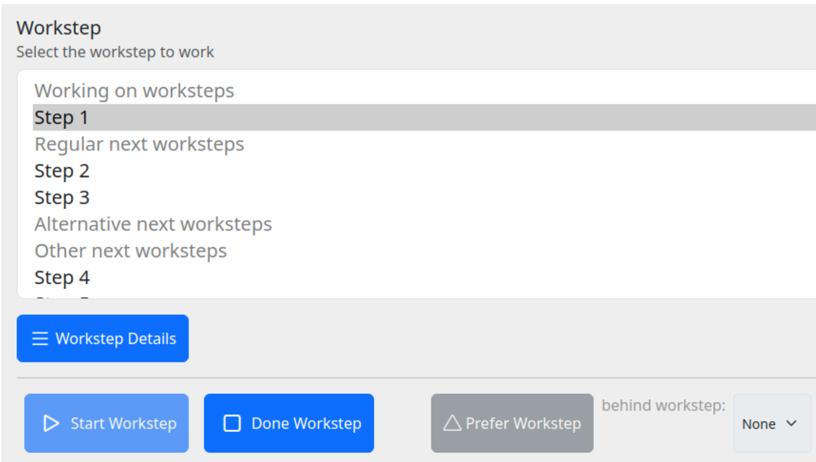

Figure 6: View of the planner on the list of available options

The tasks in each category are ordered by priority. Tasks from the category “other” can be proposed by the worker if the situation on the shop floor requires it. Figure 7 shows the view for the planner where this proposal can be accepted or rejected.

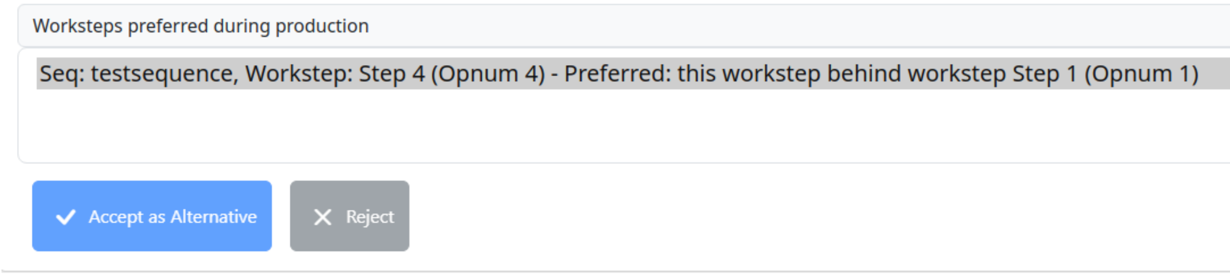

Figure 7: View of the planner on a proposed new alternative workstep

5. Conclusion

This work provides an overview of the ongoing development of the MNP. Both the XOR decision and the human-centred extension are based on user feedback and field testing. They help to make the concept more practical and efficient from a user perspective. New issues raised by Industry 5.0 are taken into account. Still the MNP is a complex concept which requires extensive manual preplanning. Therefore, its main field of application is the repeated assembly of complex structures where the planning effort as well as the advantage in efficiency are in a reasonable balance.

Although the MNP method is mainly suitable for manually manufactured large products with complex assembly sequences, the introduced extensions allow the use of MNPs in other application areas.

Acknowledgements

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Biography

Roland Larek (*1977) is head of the Production technology lab (PTL) at Hochschule Wismar, University of Applied Sciences, Technology, Business and Design, since 2013. Prof. Dr.-Ing. Roland Larek was a Research Affiliate of the International Academy for Production Engineering CIRP (2008-2013). He has been project leader for several publicly funded research projects dealing with the Maximal Network Plan and other topics in the context of digitalisation in industry.

Jan Cetric Wagner (*1989) studied and worked as a research assistant at Hochschule Wismar. He completed his doctorate in Computer Science at the Julius-Maximilians-University Würzburg in 2023. Dr. Wagner is employed as a project manager at the CIM – Innovation and Technologie gGmbH in Wismar. He conducts research on the development of MNP and digitalisation in small and medium-sized enterprises (SME).

Peter Hein (*1986) studied Automation Technology at Technical University of Dresden. He currently is a research assistant at Hochschule Wismar and is working in an application project of the MNP for knowledge transfer in SME. The introduction of XOR decisions has been developed in this project.

Hendrik Folkerts (*1987) studied Electrical Engineering at Hochschule Wismar and completed his doctorate in Computer Science at Technical University in Clausthal. He currently is a research assistant at Hochschule Wismar. Dr. Folkerts is developing the MNPplan software tool for the application of the Maximal Network Plan in work planning. The human centred extension has originated from a use case related to this work.