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Procedia CIRP 120 (2023) 1125–1130

www.elsevier.com/locate/procedia

56th CIRP Conference on Manufacturing Systems, CIRP CMS '23, South Africa

Planning and Multi-Objective Optimization of Production Systems by means of Assembly Line Balancing

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Abstract

The ever-shorter time to market demanded by customers and an increasing number of variants lead to high-frequency product development and production system planning cycles. This article therefore presents an approach that aims at increasing efficiency in the repetitive planning of variant-specific assembly systems. Compared to the state-of-the-art manual, document-based planning prevailing in industry, formal optimization methods have the potential of considering multiple optimization criteria. This article therefore proposes an approach for assigning individual process steps to stations for a given customer cycle time while minimizing the number of stations as well as optimizing additional criteria such as increasing the production system flexibility, achieving good ergonomics or reducing the deviation within provided tolerances. The solution space of the optimization is constrained by the mathematical modeling of a limited number of stations. The *operations research* (OR) model developed for this purpose considers given assembly precedence graphs as an input and includes variables, parameters, objective function and constraints. Especially the latter considers the process precedence relations in terms of the *Assembly Line Balancing* (ALB) problem as well as a divisibility of process steps. The approach is applied to the variant-specific planning of a highly automated welding assembly in the automotive supplier industry as use case. The results show its applicability and potential in reducing planning time.

Keywords: Production System Planning, Operations Research, Assembly Line Balancing.

1. Introduction

Individualization and mass customization are leading to an increasing number of product variants for manufacturing companies. At the same time, an ever shorter time-to-market is necessary to satisfy customer requirements. This results in higher frequency and shorter product development and production planning cycles. [1] Here, under high cost pressure, at very high production volumes and with little influence on the product design, automotive suppliers often plan a variant-specific production system for manufacturing and assembly of a customer variant [2]. Therefore, the research subject of this article is the rough planning of a variant-specific production line. Here, with line balancing in industrial practice, the following problems occur: First, planning is done manually and requires a lot of experience. Second, the document-based planning (in an spreadsheed software such as MS Excel) requires a lot of time and lastly the production cost estimation to the customer does not consider further optimization criteria. To address these obstacles and save cost and time, human assistance in production system planning is necessary [2]. This article therefore presents an approach to assisted production planning and multi-objective optimization with a focus on station assignment and sequencing of joining tasks by means of *Assembly Line Balancing* (ALB). For this purpose, methods of *Operations Research* (OR) are used. The presented methodology is applied to the use case of an automotive supplier and the developed OR model is presented as a result. The approach reduces human efforts in planning, explicitly optimizes several criteria (what is not possible for humans manually) and thus leads to better, comparable results.

Sec. 2 provides an overview over relevant fields of action and literature covering a classification of the considered planning task in the general planning process, related OR problems and the state of the art regarding ALB. Sec. 3 builds on the identified research gap, describes the fundamental problem, and proposes four methodological key questions to solve the problem. An introduction to the use case and a presentation of the the developed OR model are outlined in Sec. 4. Sec. 5 summarizes this article and gives an outlook on further research.

10.1016/j.procir.2023.09.136

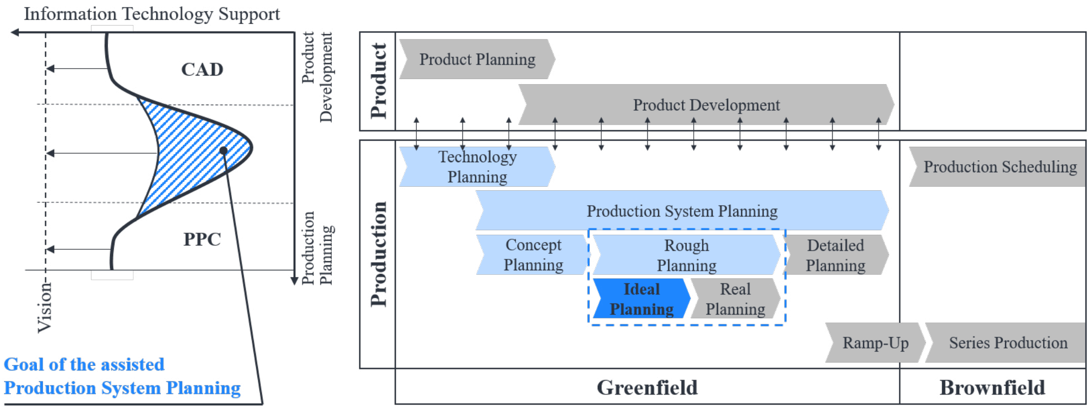

Fig. 1. Left: Degree of Information Technology Support. Right: Classification of this Article in the Production System Planning Process.

2. Fields of Action

2.1. *Assisted Production Planning*

Overall, the approach described in this article aims at closing the gap between product development and production planning (see Fig. 1). Thereby, the approach shall assist humans in the variant-specific rough, ideal greenfield planning of new production systems. In literature, there are several approaches dealing with assisted production planning: Fallböhmer introduces the idea of technology chains that can be derived from product data [3]. This concept is taken up by many (such as [4] or [5]) in order to plan process sequences. Trommer describes these as process precedence graphs [6]. However, such graphs only include precedence relationships and therefore provide for many different resource-based sequences. Hagemann for example deals with the assignment of process steps to stations [7].

The results of a comprehensive literature study on assisted production planning are shown in Table 1. With Schaefer et al. we introduce a holistic approach to assisted production planning directly based on product data including human experiential knowledge [2]. This article now complements this approach and focuses on optimizing the resource sequence based on previously derived process precedence graphs. The resulting allocation problem by means of ALB can be solved using OR methods.

Table 1. Approaches for Assisted Production System Planning.

Legend:
● regarded
◐ rudimentary regarded
○ not regarded

		Product data	Expert knowledge	Process sequence	Ressource-based
[3]	Fallböhmer (2000)	●	○	●	○
[6]	Trommer (2001)	●	○	●	●
[8]	Niu et al. (2003)	●	○	●	○
[9]	Müller (2008)	◐	●	◐	●
[10]	Su (2009)	●	○	●	○
[11]	Ou & Xu (2013)	●	○	●	○
[12]	Wang & Tian (2016)	◐	○	●	○
[13]	Müller (2018)	◐	○	◐	◐
[5]	Jacob et al. (2018)	●	◐	●	◐
[14]	Hermann (2019)	◐	●	●	○
[15]	Neb & Bauernhansl (2021)	●	○	●	◐
[7]	Hagemann (2022)	◐	○	◐	●
[2]	Schäfer et al. (2022)	●	●	●	●

2.2. *Operations Research*

In general, OR refers to the the use of mathematical methods for decision support [16]. In literature, there are several ways of clustering OR problems and methods, one classifying general ALB as *Mixed-Integer (Non-) Linear Programming*. At its core, ALB describes an assignment problem. Well-known and thoroughly researched examples of assignment problems are (I) bin packing, (II) the general transport problem and (III) the resource allocation problem. (I) denotes the assignment of a number of packages to containers whilst minimizing the number of containers [17]. With (II), supply and demand are matched while minimizing the resulting transportation costs between sites [18]. In (III) tasks are assigned to people/resources with the aim of reducing costs [19]. With ALB, additional constraints are introduced: When assigning assembly tasks to stations, previously established assembly precedence graphs must be taken into account, thus limiting the assignment options [20].

2.3. *Assembly Line Balancing*

Assigning process steps to stations is a crucial task in planning as well as scheduling. Table 2 summarizes several approaches addressing this task. The first investigations of [21] take place in the 1980s. Most approaches to ALB and ALD optimize either the number of stations or the resulting production costs. This article also draws inspiration from production scheduling, where Roth et al. for example introduce an approach for energy-oriented order planning [22]. Latest research in ALB by Albus & Seeber focuses on a dynamic selection of resources [23].

Table 2. Approaches for Solving the Resource Allocation Problem.

ALB: Assembly Line Balancing
ALD: Assembly Line Design
JSS: Job Shop Scheduling

		Application area	Divisibility of tasks	Criteria of the objective function
[21]	Ghosh & Gagnon (1989)	Alb	○	stations
[24]	Rubinovitz et al. (1991)	Ald	○	tpt. time
[25]	Bukchin et al. (2000)	Alb/d	○	costs
[26]	Pastor et al. (2002)	Alb	○	costs
[27]	Boysen (2005)	Alb/d	○	different
[28]	Rekiek et al. (2006)	Ald	○	multiple
[29]	Mas et al. (2016)	Ald	○	costs
[30]	Huang et al. (2018)	Jss	○	multiple
[22]	Roth et al. (2021)	Jss	○	energy
[23]	Albus & Seeber (2021)	Alb	○	costs

Legend: ● regarded ◐ rudimentary regarded ○ not regarded

2.4. Summary of Related Work

There is a need for supporting humans in production planning, to reduce planning time and ultimately maximize efficiency (see Sec. 1). In literature, there are a number of articles dealing with assisted production system planning. However, Sec. 2.1 shows that most of them do not combine deriving process sequences with assigning these process steps (tasks) to resources (stations). This article uses previously generated assembly precedence graphs (see [2]) and aims at optimizing the resulting production system by means of ALB. Here, methods of mathematical optimization (OR) can be used (see Sec. 2.2), whereby a multi-objective optimization (which considers several/different optimization criteria) is of central importance. With ALB and especially with the application example of this article, it may now be necessary to split the process steps in resource allocation. However, approaches that consider a divisibility of tasks to be assigned in mathematical optimization do not yet exist - even in other application areas (see Sec. 2.3). In order to close this gap, this article proposes a mathematical model considers all of the above. At first however, in the following section the underlying problem is characterized and described in more detail.

3. Problem Description and Methodical Approach

This section gives a detailed description of the station assignment problem (Sec. 3.1) and presents a transferable approach to dealing with such problems (Sec. 3.2). This is then applied in Sec. 4 using a concrete example from industry.

3.1. Problem Description

As described in Sec. 2.3 and visualized in Fig. 2, ALB basically deals with the assignment of tasks (white) to stations (blue & red). Here, certain restrictions must not be violated.

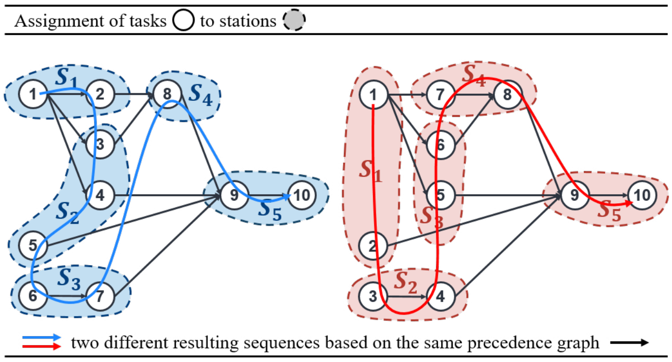

Fig. 2. Visualizing the Allocation Problem by means of ALB.

These restrictions result from e.g. the type of the task/station as well as the so-called *assembly precedence graph*. This contains precedence relationships between the individual process steps in the form of simple structures, branches or mergers [31]. Categorically, Boysen et al. distinguishes here between the assignment of tasks to stations: [20]

- I: **for a given cycle time with the aim of minimizing the number of stations**;
- II: with the aim of reducing the cycle time;
- E: with the aim of reducing the number of stations and the cycle time;
- F: the cycle time and the number of stations are fixed.

This article deals with a category I problem. In this task, it should be noted that an assembly precedence graph usually allows several different, resulting assembly sequences, as Fig. 2 shows using a simple example. Thus, the so-called *traversing* deals with the determination of the *optimal* resulting sequence based on the constraints of the graph. Amongst other things, to answer the question *"what exactly is optimal?"*, a methodical approach to model the described problem is presented below.

3.2. Methodical Approach

In order to now find optimal solutions to the problem described above, it helps to consider the following key questions:

1. What to improve?
2. What can be changed to improve?
3. What is given?
4. Which environmental influences must be considered?

First, it must be clarified what is to be improved by the optimization. This could be for example costs, time or quality. There can also be several objectives simultaneously. These objectives must be evaluated in their relevance in order to later create a weighted objective function with more objectives. Then it must be investigated which parts of the system can be changed in order to improve the system. This leads to **variables**, which are arbitrary and changeable values. They need to be calculated as a solution within the framework of the optimization. Next all values which are given due to the components selection are collected. Those given values can be defined as **parameters**, which are arbitrary but fixed values. They serve as input values in the optimization and are determined and defined through previous process analyses. After the parameters and variables are defined, the belonging **objective function** can be derived. Finally, the environmental influences of the real problem must be considered. These flow into the model as so-called **constraints**. They restrict the solution space of the model. The restrictions can be in the form of equations and inequalities.

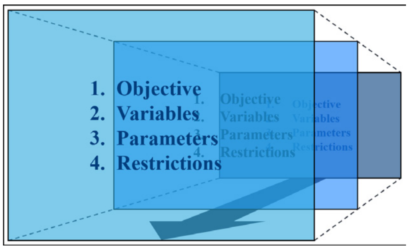

Fig. 3. Methodical Procedure for an Incremental Modeling of the Problem.

Answering these four key questions will lead to an overview of the problem. Starting with the most important objective, one receives a minimum viable model. This resulting basic model can then be extended incrementally (see also Fig. 3). For this, the next objective in the priority list is selected. This is either weighted in the objective function or implemented as an additional constraint in the model. It therefore creates a larger and more complex model by increasing the number of objectives.

4. Application and Modeling

4.1. Introduction of Use Case

In the automotive supplier industry, customized products are manufactured and assembled in large quantities over many years on specifically planned production lines. The present use case deals with the variant-specific planning of a weld assembly sequence for twist beam axles. The planning process [2] and the product [32] are introduced by Schaefer et al. After the necessary process steps are identified in a product analysis, the main task of the planners is to select the required resources and to optimally balance the resulting assembly line e.g. by splitting weld seams across stations. The target cycle time is given by customer demand and available production time and must be undercut. Currently, the planner uses Excel to assign all tasks to stations. Here, it is impossible to manually optimize multiple criteria simultaneously, which is why we suggest an OR model.

4.2. Introduction of Model

Following the method from Sec. 3.2, first, the objectives of the problem are defined. In this use case the main focus lies on minimizing the total cost of production. Next to this, the flexibility of the system should be maximized. The quality of the twist beam axles should be improved while at least meeting a minimum standard. Also to protect the employees and comply with legal regulations, ergonomic aspects should be incorporated. As shown above, the planning is under strong cost pressure, which is why the cost objective is rated as most important. The additional objectives can then gradually complement the model.

(P1) Minimizing costs: The main cost drivers in this use case are the different stations. Here, there are two decisions to be made: First, the suitable stations need to be selected by means of opening a station of a specific kind, denoted by a binary variable:

$$\gamma_{jk} = \begin{cases} 1 & \textit{if the station j from type k is opened} \\ 0 & \textit{else} \end{cases} \tag{1}$$

Second, x_{ijk} denotes the proportional assignment of task i to an opened station j of the type k:

$$x_{ijk} \in [0, 1] \tag{2}$$

In total, there is a **set I of tasks** i that have to be assigned. Each task has a certain processing time, which in this case is determined by the weld seam length and the welding speed. The order of the tasks is technically limited and is described by a precedence graph. The **set M of precedence relations** can be represented using a matrix, as shown in Fig. 4.

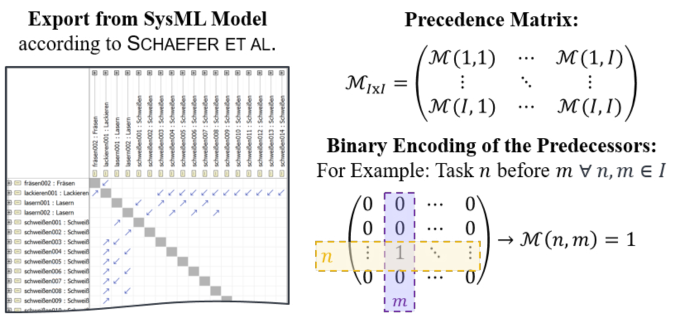

Fig. 4. Assembly Precedence Graph represented using a Matrix.

In addition, there is a **set J of stations** j. The individual stations can be of different types. The type of a station is indicated by the index k. **K is the set of station types**. Within the application example, the stations differ according to the number of welding robots (1 or 2), the periphery (with or without turntable) and the type of handling (human or robot). These three criteria affect the machine cycle times and costs, as illustrated in Fig. 5.

Looking at the **objective function**, the total costs result from the sum of fixed costs f_{jk} and the sum of variable costs c_{ijk} that depends on the time of the proportionally assigned task(s).

$$\min \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} c_{ijk} + \sum_{j \in J} \sum_{k \in K} f_{jk} * \gamma_{jk} \tag{3}$$

After defining the the variables and parameters as well as the objective function, now the environmental and technical restrictions need to be considered. In this basic model, a first set of constraints is defined as follows: (4) Completeness of tasks over all stations, (5) maximum cycle time, (6) limitation

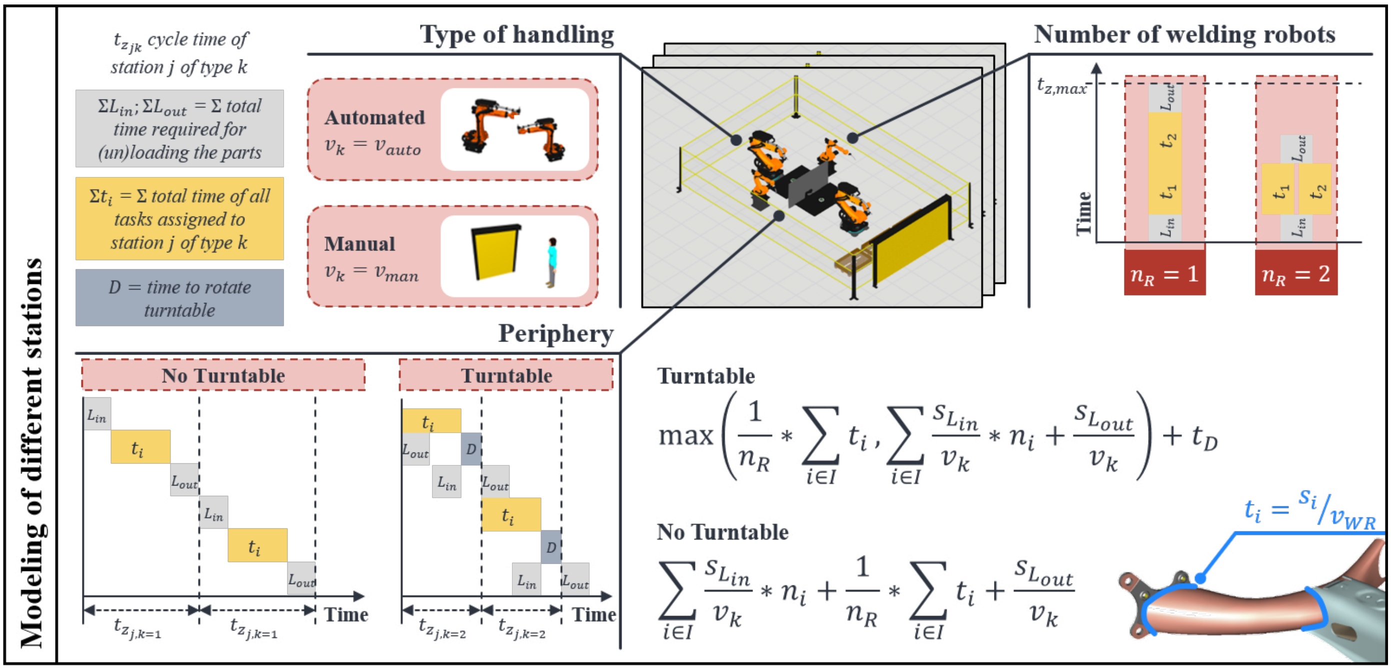

Fig. 5. Mathematical Modeling of different Stations and necessary Data Input: With regards to the planned quantitative application example, the process times for welding for example are derived from the weld seam lengths and the welding robot speed. For all other handling times, etc., experience-based values and log data from production can be used (e.g. loading and unloading or turntable rotations). All necessary data inputs are available. For further input/output see Schaefer et al. [2]

of divisibility, (7) only one type for each station, (8) technical predecences and (9) equipment feasibility:

$$\sum_{j\in J} x_{ij} = 1 \forall i \in I \tag{4}$$

$$t_{z,jk}(d_{ij}, B_{ijk}, E_{ik}, D_k) \leq t_{z,max} * \gamma_{jk} \forall j \in J \forall k \in K \tag{5}$$

$$d_{ij} \geq d_{i,min} * \gamma_{jk} \forall i \in I \forall j \in J \tag{6}$$

$$\sum_{k\in K} \gamma_{jk} \leq 1 \forall j \in J \tag{7}$$

$$0 = \sum_{j=0}^{r} x_{mj} * (1 - \sum_{j=0}^{r} x_{nj}) * M(n,m) \forall i = n, m \in I \forall r \in J \tag{8}$$

$$\gamma_{jk} * F(i,k) \geq x_{ij} \forall i \in I \tag{9}$$

(P2) Maximizing flexibility: Now that the basic model is established, a second objective is added and flexibility is considered as the quantitative overcapacity of a system. In this case, the total space utilisation is used for quantification. Minimizing land use leads to more open space and thus to increased flexibility. This optimization is influenced by γ_{jk}. The different base areas A_{jk} of the station types k must now be used as further parameters. A natural restriction resulting from the new objective is that the maximum available area must not be exceeded. This now results in the second objective function 10 and a further restriction 11:

$$\min \sum_{j\in J} \sum_{k\in K} A_{jk} * \gamma_{jk} \tag{10}$$

$$\sum_{j\in J} \sum_{k\in K} A_{jk} \leq A_{total} \tag{11}$$

(P3) Improving ergonomics: The main focus/objective of the topic "ergonomics" is to protect the employees. It is also important due to legal restrictions, which can differ between countries. Usually Occupational Health and Safety Acts only give a weight-related upper bound one person can carry without suffering from long-term health restrictions. Since this restriction only affects the decision of the station type k (automated or manual handling), no new variable is needed. However, additional parameters are required: First, the weight of new parts assembled within task i defined as w_{ij} and second, the maximum weight considered as w_{crit}. To follow regulations, another constraint (12) can be added to the problem:

$$w_{ij} \leq w_{crit} \forall j \in J \forall k \in \textit{human handling} \tag{12}$$

Outlook on further problems: This paragraph outlines some other problems relevant to the described use case. For example, different dimensional tolerances of weld seams directly influence the production sequence. To meet quality standards, a weld seam with high tolerance requirements should be executed a the end of the assembly line to avoid distortions caused by subsequent tasks. This could be implemented as a second, weighted precedence graph. Furthermore the consideration of installation space and part dimensions could limit the assignment of tasks to stations.

Resulting model: In order to unite all sub-problems in an overall model, the individual objective functions f_n need to be weighted. Weights are implemented as α_n resulting in an overall objective function (13). The constraints from each sub-problem can be added to restrict the solution space (14):

$$\min \alpha_1 * f_1(x_{1...m}) + \alpha_2 * f_2(x_{1...m}) + ... + \alpha_n * f_n(x_{1...m}) \tag{13}$$

$$s.t.\ Ax \leq b \tag{14}$$

5. Summary and Outlook

This article deals with the goal of assisted production system planning. A complex and usually time-consuming task here is the planning and optimization of variant-specific assembly lines by means of ALB. With the application partner - a large automotive supplier - to date, this is being done manually. Therefore, it is impossible to manually optimize several target variables at the same time. For this reason, the article presents a transferable method for abstracting and modeling such problems. This is applied to the planning of a welding assembly line and the underlying resource allocation problem is captured incrementally resulting in a multi-objective optimization. The overall model takes into account the specific constraints and explicitly optimizes the given objectives. The application of OR methods can thus contribute to the big picture of assisted production planning (as described in [2]) and eventually reduce planning time.

Future research will focus on the implementation of the presented approach in order to quantify the benefits. The model will be implemented with the python package Gurobi and will be available open-source on gitlab in the long run. A validation through a comparison of the results with human planning approaches is also planned, demonstrating the advantages mentioned above. In addition, the approach can be adapted to mixed-variant assembly lines, where the objective function could use variant flexibility, i.e. the number of different variants that can be produced in one station. Likewise, the results of the optimization shall be visualized in an automated manner (using a 3D-simulation software such as Visual Components) in the future to serve as a basis for subsequent detailed layout planning.

Acknowledgements

This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program [grant number 873111].

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