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Optimization Model for Identification of Assembly Alternatives of Large-Scale, Make-to-Order Products

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Abstract**—**Assembling large-scale products, such as airplanes, locomotives, or wind turbines, involves frequent process interruptions induced by e.g. delayed material deliveries or missing availability of resources. This leads to a negative impact on the logistical performance of a producer of xxl-products. In industrial practice, in case of interruptions, the identification, evaluation and eventually the selection of an alternative order of assembly activities ('assembly alternative') leads to an enormous challenge, especially if an optimized logistical decision should be reached. Therefore, in this paper, an innovative, optimization model for the identification of assembly alternatives that addresses the given problem is presented. It describes make-to-order, large-scale product assembly processes as a resource constrained project scheduling (RCPS) problem which follows given restrictions in practice. For the evaluation of the assembly alternative, a cost-based definition of the logistical objectives (delivery reliability, inventory, make-span and workload) is presented.

Keywords**—**Assembly scheduling, large-scale products, make-to-order, rescheduling, optimization.

I. Introduction

A. Characterization of Large-Scale Products

LARGE-scale products are typically characterized by a demanding structural and technological complexity, their large dimensions and a heavy weight [1]-[4]. According to a definition by the IPH in Hanover, the production costs of large-scale products increase over-proportionally relative to the further increase of a particular characteristic product feature, such as the size or the range of functions [5]. Using this definition, production research tries to distinguish large-scale products from 'regular' or miniature products. Examples for large-scale products are trains, large special machinery or wind energy plants [6]-[8]. What these large-scale products also typically share is a high product variance and a large proportion of customized features [8]. Accordingly, they are basically always produced in a make-to-order setting.

B. Characterization and Consequent Challenges of the Assembly of Large-Scale, Make-To-Order Products

Introduced by the special characteristics of large-scale products, the assembly process includes strong specific features as well. As the markets for large-scale products are typically limited regarding their size, the overall production only yields low volumes as its output. In low-volume assembly, certain disadvantages compared to high-volume assembly exist: Market power with regard to the inbound supply chain is limited [9]. Additionally, most processes are less standardized and the repetition rate is small [10]. This also results in a low planning quality as the limited production volumes prohibit high planning costs [11].

The assembly of large-scale products is generally organized in on-site assembly or fixed station assembly to allow for the high product variance [12]. Major challenges of large-scale assembly include high production costs, frequent product modifications even after the start of assembly, and an insufficient availability of data [12]-[14]. In combination with external supply shortages and delays, frequent interruptions of the assembly process are the consequence, resulting in the requirement for rescheduling the processes to nevertheless adhere to delivery due dates and avoid contract penalties for late delivery [15], [16]. The large product size and the resulting need for space is a major bottleneck of production as companies provide for adequate areas. However, the information about the resulting need for space is often not available or it requires a high effort in data generation in practice [12].

C. Assembly Objectives of Make-To-Order, Large-Scale Products

Interruptions influence the logistical objectives. The objectives of assembly process are equal to the logistical objectives of manufacturing, described by the logistical objective system of Wiendahl who introduced the two dimensions logistic performance and logistic costs [17]. Logistic performance is determined by the delivery reliability and the make-span. Typically, a short make-span corresponds to high delivery reliability - however, too early completions of orders influence logistical objectives as well. This is supported by low inventory and WIP levels. Logistic costs, on the other hand, consist of the cost of holding capital and process costs. Low capital costs require low stocks of raw materials, semi-finished and finished products. The process costs, however, depend on the workload of the assembly system. High WIP levels result in a high level of workload of the assembly system. Accordingly, the logistical objectives delivery reliability, inventory/WIP, make-span and workload strongly interact with each other [18]. Assembly especially focuses on delivery reliability and make-span [19].

In research, the mentioned logistical objectives are usually time-based [20]. The deviation of delivery reliability is the difference between end of production and the due date of the product. The inventory corresponds to the sum of all waiting

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activities. If set-up times are included in processing times of activities, then cumulative waiting times of activities and their processing times define the make-span. The workload is the ratio of all processing times of activities which have to be processed and the available capacity of a resource in a defined time period. Hence, minimizing waiting times influences the logistical objectives: Delivery reliability, inventory/WIP and make-span. Minimizing waiting times increases workload as well, because in case of interruptions a troubled assembly process (‘activity’) is replaced so that the standstill of the assembly system is prevented.

If all four logistical objectives are considered in a time-based manner for the comparison of assembly sequence alternatives, a decision for one of the assembly sequence alternatives is not yet rendered possible. The reason is because no statement can be made on which logistical objective is more important than another [21]. Therefore, a consistent, one-dimensional estimation of the logistical objectives is necessary – assembly logistic costs. In this way, each logistical objective has to be represented in terms of costs. Thus, the interaction of the logistical objectives is represented by the relation of cost rates. For the purpose of this research, we suggest the following cost representation of the logistical objectives:

Central elements of the cost-based delivery reliability are deviations which can be evaluated with penalties. Capital holding costs, which include material cost and interest rate, are the foundation for inventory/WIP and make-span. Idle time costs are the basis of the workload and contain machine and resource (personnel) cost. In consideration of interruptions during assembly processes, a successful rescheduling framework ensures minimal deviations from the achievement of the mentioned objectives.

D. Rescheduling Framework

In practice, uncertainty respectively unexpected events (‘interruptions’) typically lead to invalid assembly plans. A list of possible disruptions during the execution of an assembly plan is shown in [20], [22]. The repairing process of an invalid assembly plan in response to new conditions is called rescheduling [22]-[24]. A comprehensive framework for rescheduling research is shown in [22]. The framework includes rescheduling environments, rescheduling strategies and policies, and rescheduling methods (Table I).

The *rescheduling environment* determines the set of activities that have to be scheduled, which is static when considering a finite set of activities and dynamic when considering an infinite set of activities [25], [26].

A *rescheduling strategy* describes whether (predictive-reactive) or not (dynamic) an assembly plan is (initially) generated [22]. Both rescheduling strategies (predictive-reactive or dynamic) can be used in any reschedule environment. However, the predictive-reactive strategy (generating and updating an assembly plan) is most commonly used in practice [22].

A *rescheduling policy* specifies when rescheduling should occur. A periodic policy reschedules an assembly plan periodically [27], [28]. An event-driven rescheduling occurs triggered by a specified event and is generally used in a static environment [29], [30]. A hybrid reschedule policy is a mix of period- and event-driven policy, rescheduling an assembly plan periodically and as well when disturbances occur [31].

TABLE I
RESCHEDULING FRAMEWORK BY VIERIA [22]

Rescheduling Environments				
Static (finite set of jobs)		dynamic (infinite set of jobs)		
deterministic (all information given)	Stochastic (some information uncertain)	no arrival variability (cyclic production)	arrival variability (flow shop)	process flow variability (job shop)
Rescheduling Strategies				
Dynamic (no schedule)		Predictive-reactive (generate and update)		
dispatching rules	control-theoretic	Rescheduling Policy		
		periodic	event-driven	hybrid
Rescheduling Methods				
Schedule generation		Schedule repair		
nominal schedule	robust schedule	right-shift rescheduling	partial rescheduling	complete regeneration

Rescheduling methods define how schedules are generated and updated [25], [32]. In case of an interruption, an assembly plan becomes invalid, so the use of a schedule repair method is necessary. A right shift schedules each activity by the amount of time needed to make the schedule feasible [33]. Partial rescheduling rearranges only the activities that were affected directly or indirectly by the interruption [32], [34]. It preserves the initial schedule as much as possible. Complete regeneration reschedules each activity which has not been processed, including those activities not affected by the interruption [35], [36].

Based on the (practical) problem which is considered in this paper, the rescheduling environment is static and stochastic because of uncertainties in processing times, resource capacities and material preparations as well as a finite set of jobs. In dynamic rescheduling strategies, dispatching rules are used to control production without an assembly plan and to sort the jobs by certain criteria when a resource becomes available [22]. However, some dispatching rules require a large amount of information (sometimes with high quality) and the job priorities must be recalculated with every dispatching decision [22]. Therefore, dynamic rescheduling strategies are not common for the assembly of large-scale products (see Chapter I *A*). The advantage of a predictive-reactive strategy is the possibility to generate schedules with different priorities. The update works with the same strategy as the generation does. Therefore, a priority rule-based heuristic approach for schedule generation is able to *identify* an *assembly alternative* as well. Due to the fact that interruptions occur unforeseeably and a weekly scheduling meeting is common in industrial practice, the rescheduling policy is hybrid. It is further assumed that in case of an interruption, a schedule repair is necessary. In respect of this, there are different kinds of activity types: activities which are completed, those in progress and those which remain to be started. Here, activities which are completed cannot be scheduled again – accordingly, disassembly is not considered. For this reason, a complete regeneration of the original assembly plan is not required. In addition, complete regeneration is overly time-consuming [22]. In our approach, activities in progress are fixed within the schedule, therefore only activities which have to be started are considered and a partial rescheduling method is used. Thus, in case of an interruption the assembly will be resumed with the assembly alternative. Finally, right-shifting requires little effort and is easy to be implemented but leads to low system performance compared to more schedule changes [20]. Therefore, a partial rescheduling method should be used.

To enable a scheduling and rescheduling of large-scale product assembly, the problem must be modelled adequately, first. The question arises which problem model type is adequate for the large-scale product assembly. In literature, various approaches for modelling problems of assembly scheduling exist [37]-[39]. Here, the major assembly scheduling problem types ('Assembly Line', 'Assembly Job Shop', 'N-Stage Assembly', 'Block Assembly' and 'Resource Constrained Assembly') are discussed to finally choose a problem type that fulfills the requirements of large-scale product assembly.

E. Adequate Problem Modelling

An assembly line is a flow-orientated production system in which assembly stations are aligned in a serial manner. Assembly objects pass through the assembly stations as they are moved along the line, usually by some kind of transportation system [40]. The 'Assembly Line Problem' ('ALP') focuses on the allocation and scheduling of assembly processes by balancing assembly lines [41]. Subsequent works, however, attempted to extend the problem by integrating practice constraints, like U-shaped lines, parallel stations or processing alternatives [40], [42]. In large-scale product assembly, a (flow) assembly line is usually not given due to technical transportation difficulties and the high variance. Instead, flexible assembly areas are used in a varying sequence. The ALP problem is therefore not adequate.

The 'Assembly Job Shop Scheduling Problem' ('AJSP') is an extension of the classical job shop problem (JSP). The AJSP covers a JSP for parts manufacturing and afterwards appends one or more assembly stages [43]. This kind of assembly scheduling is called 'N-Stage Assembly Scheduling'. There, a depth of process stages that is higher than one is considered, which means that not only the final assembly is modeled, but also component assembly and especially the parts manufacturing to supply the component assembly. Flow shop [44], [45] and flexible shop [46] are common environments of parts manufacturing. As mentioned above, in large-scale product assembly, the companies often rely on their external suppliers while their power to control the external suppliers is low because of the limited volumes. Therefore, an n-stage problem modeling is not adequate as well. Especially, because the company that assembles the large-scale products cannot schedule/control suppliers. Furthermore, with respect to parts manufacturing, the flexible job shop scheduling problem ('FSJP') considers assembly jobs with specific operations, which have to be carried out on specific different machines available with the goal of finding an optimal or at least satisfying routing through the machines [47]. The flexibility of this model type fits large-scale product assembly well. However, in our application it is irrelevant case is the very limited planning degree of detail in real large-scale product assembly as introduced above.

The 'Block Assembly' is common for large-scale products like ships where the building process is comprised in on-site construction (e.g. erection) and series manufacturing (e.g. block assembly outfitting) of blocks [48]. The assembly block stage involves a series of complicated processes (e.g. fitting, welding and grinding) on a limited working area [49]. The availability of a located area of assembling one particular block, however, relies on the spatial layout of the layout area, the block dimension and equipment constraints of the workshop [50]. The 'Block Assembly Problem' ('BAP') focuses on the allocation and scheduling of assembly blocks to specific assembly areas [51]. The large-scale product assembly is generally organized in on-site assembly or fixed station assembly, where the allocation of products to a specific assembly space is practically not a relevant challenge due to insufficient data availability (see introduction above). Therefore, a block assembly problem modeling does not fit our application case either.

Finally, RCPS shall be discussed for the use in large-scale assembly. RCPS problems schedule activities of a project ('product') while given precedence constraints between the activities are satisfied. In addition, resource requirements of the scheduled activities per period do not exceed given capacity constraints for different types of resources [52] – thus, it is also well employed for rescheduling purposes [37]. Accordingly, in this paper, the large-scale product assembly is modeled as an RCPS problem.

II. Problem Description

Within the large-scale product assembly, I products are assembled according to 'assembly networks' and each product has a set of activities $j \in J$ and is denoted as PA_i. In those networks, nodes represent assembly activities and arcs represent technological precedence (no preemption) relations between activities (Fig. 1). Arcs are weighted with $tt^*_{ijs} \geq 0$, which represents transition times between activity j and a direct predecessor s. Let $Prec_{ij}$ be the set of direct predecessors of an activity j of product i and $iPrec_{ij}$ the set of all indirect predecessors and Suc_{ij} the set of all successors of activity j of product i. Every activity j of product i have a processing times p_{ij}(without intermission) and a resource requirement $r_{ij1,\dots,}r_{ijk}$ of different assembly resource types which is denoted as rRT_{ijk}. RT is a set of all $k = \{1, \dots, K\}$ renewable assembly resource types. Activity j of product i requires rd_{ijk} units of resource type k. Based on the assembly network, processing times and due dates d_i of a product i, we can calculate the earliest start times ES_{ij} and the latest start

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times LS_{ij} for all activities j of a product i by forward recursion and backward recursion [53]. In case of an interruption, if an activity j ends after the due date d_i of product i, the latest start time of the activity and the earliest and latest starting times of all technological successors have to be updated. This has to be done as well, if the difference of latest starting time LS_{ij} and scheduled starting time ts_{ij} of activity j of product i is smaller than the length of the interruption. Further, each activity has requirements of parts. Only A-parts and selected B-parts (high value parts and sourcing time) are considered.

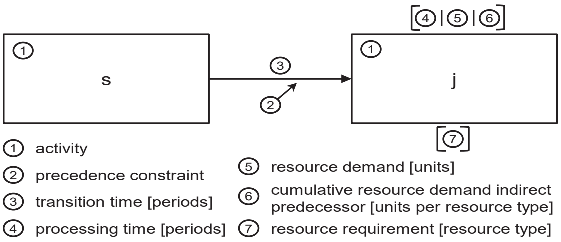

Fig. 1 Problem description

Renewable assembly resources are categorized in types such as welder, mechanical assembler, electrical assemblers and power tools (machines). Except for power tools, each assembly resource type k contains a number q of personnel with a specific work time model wtm_{kt} which depends on the period t (e. g. weeks). It is assumed that the work time model is equal for the staff of an assembly resource type in a period. Power tools have a specific available capacity per period as well. Reasons for time varying capacity is caused by un-/planned off-time of workers (fluctuation, sickness /vacation) and planned down-times of machines (inspection, repair), for example. Thus, a time varying capacity is considered and the availability of cRT_{kt} of a resource type k is the product of the work time model wtm_{kt} and the quantity q of personnel which is available in period t. In simplified terms, in each period, a defined amount of resource capacity is available. In addition, each activity j of product i requires an amount of personnel ap_{ijk} and capacity $rdRT_{ijk}$ (resource demand) of assembly resource type k. If activities have direct or indirect technological precedence relations and are scheduled in the same period, it is necessary to check the feasibility of capacitive constraints as a kind of an integrated personnel planning problem (PPP). The reason for doing this is that available capacity per period is based on the personnel work time model (1). For example: The binary variable $x_{ijkt} = 1,$ if an activity j of product i is scheduled in period t on resource type k and 0 otherwise. In case, that a predecessor s of activity j are scheduled in the same period, the difference of work time model in that period of required resource type and resource demand per personal have to be greater than the resource demand of activity s. Thus, if more than one predecessors of activity j are scheduled in the same period, the difference of work time model in that period and resource demand per personal have to be greater than the sum of all resource demands (cumulative resource demand indirect predecessor).

$$\left(wtm_{kt} - \frac{rd_{ijk}}{ap_{ijk}}\right) \cdot x_{ijkt} + \left(1 - x_{ijkt}\right) \cdot BigM \geq \sum_{s \in iPrec_{ij}}^{S} rd_{ism} \cdot x_{ismt} \qquad \forall i,j \in PA_i, k,m,t \qquad (1)$$

Fig. 2 shows an example of an assembly network with four activities and different resource requirements (rt1/rt2) and processing times, which should be scheduled in the same period. In addition, for the execution of an activity j of a product i, a specific amount of personnel $ap_{ijk} = 1$ is required. The schedule is feasible if the cumulative resource requirements of all predecessors s (activity: 1, 2, 3) of activity j (activity: 4) on assembly resource type m (with $m \in RT$) is less or equal than the difference of the work time model of assembly resource type k in period t and resource requirements per personal of activity j of product i (see (1)). In scenario (1), the work time model of resource type k is 8 hours. In scenario (2), it is 6 hours. It is assumed that for the two scenarios, for each resource type the resource requirements of the scheduled activities do not exceed the resource capacities. However, the capacity precedence constraint is not valid in scenario (2) (Fig. 3). Therefore, a scheduling of activity A1, A2, A3 and A4 in the same period is not feasible with a work time model of 6 hours for each assembly resource type. It can be specified that (equation 1) ensures a valid schedule in view of PPP.

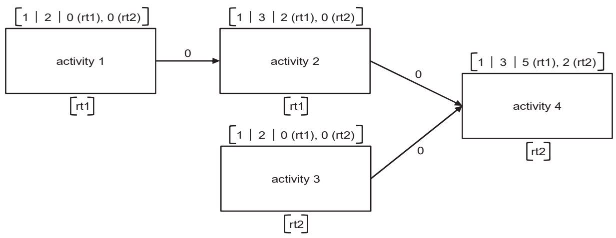

Fig. 2 Example of illustration of capacitive precedence constraint

	sum resource requirements		personnel precedence
	resource type 1	resource type 2	
scenario 1:	$8 \geq 5$ (✓)	$8 \geq 5$ (✓)	$8 - \frac{3}{1} \geq 5$ (✓)
scenario 2:	$6 \geq 5$ (✓)	$6 \geq 5$ (✓)	$6 - \frac{3}{1} \geq 5$ (×)

Fig. 3 Personnel precedence constraint

Parts which are built into end products are widely categorized according to a Pareto analysis into A-, B- as well as C-parts [54]. B- and C-parts are standard elements which are common to most of the products and are often available from stock. In contrast, A-parts as well as selected B-parts are typically manufactured or ordered for a specific customer order and are not kept on stock as well as very expensive. Therefore, especially delayed A-parts and certain B-parts may disrupt or delay the schedule and hence require special management attention [55], [56]. The timing of incoming parts is known from corresponding order documents. In this paper, in-house part manufacturing is not considered and only decisive parts, that is A-parts and certain B-parts are modeled – it is assumed that C-parts are available all the time. Before an activity can be started, all required A-parts and selected B-parts have to be available. The availability period of A-parts of activity j of product i is denoted as mp_{ij}.

In conclusion, a schedule is feasible if it satisfies the following constraints:

- Each activity j of product i has to be scheduled parallel on all required resource types and cannot be started before all its predecessors are finished, the transition time of activity j and predecessor s is elapsed, the capacity precedence is feasible and all required A-parts/ certain B-parts are available.
- Resource constraints have to be satisfied, e. g., for every period t, the sum of the resource requirements of all scheduled activities does not exceed the resource capacities.

The objective of the RCPS is to determine the start times ts_{ij} of activities subject to technological, capacitive precedence and resource constraints in a way that the sum of the logistic costs (delivery reliability, inventory, make-span and workload) of the products is minimized. The major challenge of the model described above is the integrated personnel planning problem and the optimization according to multiple cost-based objectives. The kind of problem above is similar to problems that appear in the assembly of machine tools [57]- [60], but has not yet been treated (see next chapter).

III. State of the Art

In literature, the RCPS has become a standard problem during the last decades and belongs to the class of NP-hard problems [61]. *Pritsker* developed a mathematical model [62] and *Brucker* has provided a notation to classify resource constrained schedule problems [63]. This notation follows the established three field notation alpha/beta/gamma for the machine schedule problem introduced by Graham [64].

Focus of this paper is a deterministic RCPS (no re-entrant) of activities in assembly, especially the consideration of multiple products. Therefore, the attention of the literature review is based on deterministic RCPS research. Note that the specific assembly context is not essential for the literature review, because the specific challenges of the problem may appear in other research fields. The problem in this paper is similar to the work of Kolisch, published in 2000 [57]. Therefore, the literature review focuses on relevant RCPS publications after 2000. The literature review is made in all conscience, but it does not guarantee a full range of deterministic RCPS research. However, certain trends can be recognized in RCPS research that will be discussed here. Table II gives an overview of RCPS problems categorized according to the activity concept, alternative precedence constraints, different resource concepts, objectives and applications. A general, extended survey of RCPS is shown in [65].

As seen in Table VI, most RCPSs consider the no preemption case with integer processing times for all activities and a constant resource demand. Note that if temporal constraints are observed, structural (technological) precedence constraints are unavoidable. Nonrenewable resources differ to renewable resources in the sense that their capacity is fixed (e.g. due to budget constraints) within the time horizon and are common in RCPS research. Most publications consider an available capacity of renewable resources that is constant. In industrial practice, disruptions or uncertainty (delayed material, unavailable resource capacity) occur which are not covered in those approaches yet. Moreover, it can be stated that the capacitive precedence constraints as a kind of personnel planning request have not been treated so far in RCPS research. For these reasons, the given problem of large-scale, make-to-order product assemblies has so far not been treated adequately.

The considered optimization objectives in literature are discussed in more detail based on Table VII. Each objective is categorized into time-based and monetary formulation (e.g., objective minimizing ‘weighted’ tardiness is comprehended as time-based). Except for maximizing cash flow, all monetary objective show a minimization target. Considering a problem formulated as RCPS, the most frequent objective is minimizing make-span (time-based). After this, minimizing tardiness is usually considered in RCPS. Generally, the monetary objective of maximizing cash-flow is used frequently as well. It can be stated that multiple cost-based assembly logistic objectives have not been treated so far in the context of RCPS research, especially the cost-based objective of minimizing inventory. For that reason, the objectives of the given problem above have not been considered in existing publications.

Finally, the applications of the considered works of Table VI shall be discussed. It can be stated that the combination of RCPS and multi-product case is rarely seen present in assembly scheduling research. In addition, the make-to-order environment is rarely considered either. Considering approaches, the reader of this paper is referred to the corresponding literature for a detailed approach description. Further approaches in RCPS research are described in [37], [91], [92]. With respect to the literature review, approaches for solving RCPS can be distinguished in exact approaches (BB), heuristic approaches (H) and meta-heuristic approaches (AC, (H)GA, LS, P PS, SA, TS). A heuristic is based on a problem-related experience procedure, while meta-heuristics imitate generic principles (e.g. evolution, swarm behavior) [58]. In literature, the best performing approaches for solving RCPS are two-phase metaheuristics, where the first phase computes initial solutions by a priority rule-based heuristic and the second phase applies a metaheuristic strategy (e.g. evolution, swarm behavior, foraging) for ‘final’ optimization [58]. It can be stated that for the given problem, different solving approaches are applicable and should be assessed. Here, the development of a priority rule-based heuristic is focused in further research.

From literature review, it can be concluded that the problem as outlined above has not yet been treated. In this paper, an optimization model is presented which serves as the first step for developing an approach to tackle the given RCPS problem for large-scale product assembly with capacitive personnel constraints.

IV. Optimization Model

For an optimization model, all logical restrictions have to be identified and satisfied for the given problem above. To model the resource constrained scheduling problem with integrated personnel planning problem (see Table V), we introduce the following decision variable: the binary decision variable x_{ijkt} equals 1, if activity j of product i is scheduled in period t on resource type k, and 0 otherwise. Overall the number of decision variables can be reduced by calculating the earliest and latest starting times by forward and backward recursion for each activity. Now we can formulate the optimization model with respect to indices and sets (see Table II), parameters (see Table III) and variables (see Table IV) as:

TABLE II
Indices and Sets

i	identifier for a product $i \in \{1,2,\dots,I\}$
j, s	identifier for an activity $j, s \in \{1,2,\dots,J\}$
k, m	identifier for a resource type $k, m \in \{1,2,\dots,K\}$
t	identifier for a period $t \in \{1,2,\dots,T\}$
$iPrec_{ij}$	indirect predecessors of activity j of product i
PA_i	activities of product i
$Prec_{ij}$	direct predecessors of activity j of product i
Suc_{ij}	direct successors of activity j of product i

TABLE III
Parameters

qRT_{ij}	quantity of required resource types	units
ap_{ij}	quantity of required personnel	units
$bigM$	sufficiently big number	
cRT_{kt}	available capacity of resource type	units
cDR_i	cost rate delivery reliability	€ / period
cI_{ij}	cost rate of storage (inventory)	€ / period
cMS_{ij}	cost rate of working capital	€ / period
cWL_k	cost rate workload	€ / period
d_i	due date of product	period
p_{ij}	processing time	period
mp_{ij}	date of material preparation	period
rd_{ijk}	resource demand of resource type	hours
rRT_{ijk}	$= \begin{cases} 1 & \text{if an activy j of product i requries resource type k} \\ 0 & \text{otherwise} \end{cases}$	/
tt^*_{ijs}	mean transition time	period
wtm_{kt}	work time model of resource type	units

TABLE IV
Variables

ts_{ij}	starting time of an activity j of product i
te_{ij}	ending time of an activity j of product i
x_{ijkt}	$= \begin{cases} 1 & \text{if an activity j of product i is scheduled in period t on resource type k} \\ 0 & \text{otherwise} \end{cases}$
Ys_{ijkt}	$= \begin{cases} 1 & \text{initial state of an activity j of product i on resource type k in period t} \\ 0 & \text{otherwise} \end{cases}$
Ye_{ijkt}	$= \begin{cases} 1 & \text{final state of an activity j of product i on resource type k in period t} \\ 0 & \text{otherwise} \end{cases}$
Z	Objective function (minimizing logistic costs including logistic performance)

The objective function (2) minimizes the sum of logistic cost (delivery reliability, make-span, workload and inventory). Note, if an activity j of product i is scheduled in period t on resource type k the binary variable $x_{ijkt} = 1$. Thus, if this activity is not scheduled in period t-1, the initial state of activity j is period t. Therefore, (3) determines the initial state for each activity of a product. If an activity requires more than one resource type, the quantity of initial states of an activity equals the quantity of required resource types (4). Equation (5) determines the starting time of an activity. In contrast to (3) which determines the initial state of an activity, (6) describes the final state. A number of equations have a similar structure. Equation (7) has similarities to (4) and (8) determines the ending time of an activity. Equation (9) ensures that an activity only starts once the material is available. In addition, the starting time of an activity has to be less than or equal to the latest starting time (10) and greater than or equal to the earliest starting time (11). Equation (12) ensures the technological precedence constraints and is similar to (13), which ensures the temporal precedence constraints. Equation (14) represents the capacitive precedence constraints as a kind of personnel planning problem which is explained above. Equation (15) guarantees that intermission is prohibited. The execution of an activity is only possible on required assembly resource types (16). Equation (17) schedules each activity on each required assembly resource type. Equation (18) guarantees that the amount of each activity in the assembly plan equals the sum of required assembly resource types and processing times. Equation (19) ensures that the required capacity of an assembly resource type does not exceed the available capacity in a period.

For the operational validation of the optimization model, a small instance with two products was generated. Each product includes 10 activities, whereas the parameters (‘resource demand’, ‘precedence constraints’ and so on) were set randomly. However, it was take care that the instance is feasible. The analytical model is implemented in the special optimization software GAMS. The instance was solved with CPLEX 24.2.2 in few seconds with a normal personal computer (2.5 GHz, 4GB working memory). The next step is the generation and solving of instances considering the high complexity of large-scale, make-to-order product assembly.

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TABLE V
MODEL

Objective function:

$$\min Z = \sum_{i=1}^{I} \max\{0, te_{ij=J} - d_i\} \cdot cDR_i + \sum_{i=1}^{I} \sum_{j \in PA_i} \left(te_{ij=J} - ts_{ij}\right) \cdot cMS_{ij} + \sum_{k=1}^{K} \left(\sum_{t=1}^{T} \left(wtm_{kt} - \sum_{i=1}^{I} \sum_{j \in PA_i} rd_{ijk} \cdot x_{ijkt} \right) \cdot cWL_k \right) + \sum_{i=1}^{I} \sum_{j \in PA_i} \left(ts_{ij} - mp_{ij}\right) \cdot cI_{ij} \quad (2)$$

In consideration of the restrictions:

Determination start and end times		
$x_{ijkt} - x_{ijkt-1} \le Ys_{ijkt}$	$\forall i, j \in PA_i, k, t$	(3)
$\sum_{k=1}^{K} \sum_{t=1}^{T} Ys_{ijkt} = qRT_{ij}$	$\forall i, j \in PA_i$	(4)
$ts_{ij} = \frac{\left(\sum_{t=1}^{T} Ys_{ijkt} \cdot t\right)}{qRT_{ij}}$	$\forall i, j \in PA_i$	(5)
$x_{ijkt} - x_{ijkt+1} \le Ye_{ijkt}$	$\forall i, j \in PA_i, k, t$	(6)
$\sum_{k=1}^{K} \sum_{t=1}^{T} Ye_{ijkt} = qRT_{ij}$	$\forall i, j \in PA_i$	(7)
$te_{ij} = \frac{\left(\sum_{t=1}^{T} Ye_{ijkt} \cdot t\right)}{qRT_{ij}}$	$\forall i, j \in PA_i$	(8)
Resource constraints		
$ts_{ij} \ge mp_{ij}$	$\forall i, j \in PA_i$	(9)
$ts_{ij} \le LS_{ij}$	$\forall i, j \in PA_i$	(10)
$ts_{ij} \ge ES_{ij}$	$\forall i, j \in PA_i$	(11)
$\left(ts_{ij} + p_{ij}\right) - 1 \le ts_{is}$	$\forall i, j \in PA_i, s \in Suc_{ij}$	(12)
$\left(te_{ij} + tt^{*}_{ijs}\right) \le ts_{is}$	$\forall i, j \in PA_i, s \in Suc_{ij}$	(13)
$\left(wtm_{kt} - \frac{rd_{ijk}}{ap_{ijk}} \right) \cdot x_{ijkt} + \left(1 - x_{ijkt}\right) \cdot BigM \ge \sum_{s \in iPrec_{ij}}^{S} rd_{ism} \cdot x_{ismt}$	$\forall i, j \in PA_i, k \in rRT_{ijk}, m \in rRT_{isk}, t$	(14)
Activity concept		
$te_{ij} - ts_{ij} + 1 = p_{ij}$	$\forall i, j \in PA_i$	(15)
$x_{ijkt} \le rRT_{ijk}$	$\forall i, j \in PA_i, k, t$	(16)
$x_{ijkt} = x_{ijmt}$	$\forall i, j \in PA_i, k, m \neq k, t$; $AnzRT_{ij} > 1$	(17)
$\sum_{k=1}^{K} \sum_{t=1}^{T} x_{ijkt} = qRT_{ij} \cdot p_{ij}$	$\forall i, j \in PA_i$	(18)
$\sum_{i=1}^{I} \sum_{j=1}^{J} x_{ijkt} \cdot rd_{ijk} \le cRT_{kt}$	$\forall k, t$	(19)

V. Summary and Outlook

In this paper, an optimization model for the identification of assembly alternatives for large-scale products has been developed. First, the characteristics of large-scale products and their corresponding assembly processes have been described. Complex product structures and unexpected interruptions within the assembly process steps due to missing material or personnel are some of the major challenges. To address these challenges, a number of rescheduling approaches have been developed in literature. It could be demonstrated that the problem at hand can be classified as an RCPS problem. State of the art solutions to handle RCPS problems have been analyzed in this paper. It can be stated that capacity precedence constraints for personnel planning have not been included in RCPS research so far. Furthermore, the cost-based description of the logistical objectives is not represented adequately. For those reasons and due to the major challenges of large-scale product assembly, a new optimization model for the identification of assembly alternative in the context of large-scale product assembly has been developed. The developed model is designed for make-to-order, multi-product assembly processes and includes activities without preemptions, resource constraints in terms of structure, material, time and capacity, different resource types as well as multiple cost-based objectives.

The developed optimization model will be used within the research project “Adaptive assembly for large-scale products”, conducted by IPH Hanover and WZL of RWTH Aachen University. The goal of the research project is to develop a methodology to illustrate, assess and evaluate assembly alternatives in order to find the most suitable assembly alternative in case of interruptions within the assembly process of large-scale products. A key element for the project is the application in industrial practice. The high level of customization of large-scale products, frequent product modifications and a low level of product and production process data define specific requirements for a scheduling methodology. Therefore, besides the optimization approach, a heuristics approach is developed that does not necessarily find an optimized assembly alternative but needs less informational input for its implementation. Here, a priority rule based scheduling heuristic is developed for several reasons: (1) it is intuitively and easily to use, (2) it is fast in terms of computational efforts and (3) a multi-rule implementation is possible and (4) no need of 'final optimization' [63]. The heuristics approach will be presented in the next publication for the above described RCPS problem. In this publication, it will also be assessed to which degree assembly alternatives differ when both the optimization and the heuristics approach are applied and how suitable each approach is for the given problem. By this comparative approach, an applicable solution for industrial practice can be determined.

TABLE VI
LITERATURE REVIEW IN RCPS RESEARCH

Attribute	Property	Unit	[66] (1993)	[67] (1994)	[68] (1995)	[38] (1996)	[60] (1996)	[58] (1997)	[57] (1999)	[69] (2000)	[70] (2000)	[71] (2000)	[73] (2001)	[74] (2002)	[75] (2002)
Activity concept	non-preemption	yes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	?
	demand	const.	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓
	multi-mode	yes		✓		✓			✓		✓			✓	
	Processing time	int.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Resource constraint	structure	yes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	material	yes					✓	✓		✓					
	temporal	yes			✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	capacitive/ personnel	yes													
Resource concept	renewable	yes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
	nonrenewable	yes		✓	✓				✓				✓	✓	
	double	yes			✓										
	availability	const.	✓	✓	×	✓	×	×	✓	×	✓	✓	✓	✓	✓
Objective	time-based	yes		✓	✓		✓	✓	✓	✓	✓	✓	✓		✓
	monetary-based	yes	✓	✓		✓								✓	
	multiple	yes	✓	✓		✓	✓	✓						✓	
Application	approach	(**)	e)	e)	e)	e)	h)	e)	e)	f)	e)	b)	b)	j)	a)
	multi-product	yes					✓	✓		✓	✓				
	assembly	yes					✓	✓		✓					
	mto	yes					✓	✓		✓		✓	✓		

Attribute	Property	Unit	[76] (2003)	[77] (2004)	[78] (2007)	[80] (2007)	[81] (2008)	[82] (2009)	[84] (2010)	[85] (2010)	[87] (2010)	[88] (2013)	[89] (2014)	[90] (2015)	[*] (2015)
Activity concept	non-preemption	yes	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	✓
	demand	const.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	multi-mode	yes	✓						✓	✓					
	Processing time	int.	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Resource constraint	structure	yes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	material	yes													✓
	temporal	yes										✓			✓
	capacitive/ personnel	yes													✓
Resource concept	renewable	yes	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓
	nonrenewable	yes	✓		✓			✓	✓	✓					
	double	yes	✓							✓					
	availability	const.	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	×
Objective	time-based	yes	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
	monetary-based	yes									✓	✓			✓
	multiple	yes									✓		✓		✓
Application	approach	(**)	i)	f)	j)	c)	d)	d)	c)	d)	e)	e)	f)	d)	e)
	multi-product	yes						✓			✓				✓
	assembly	yes			✓										✓
	mto	yes											✓		✓

Legend	Signs		Wording		Approaches Abbreviation (**)					
	✓	fulfilled	const.	constant	a)	Ant Colony (AC)	e)	Heuristic (H)	i)	Simulated Annealing (SA)
	×	opposite	int.	integer	b)	Branch & Bound (BB)	f)	Local Search (LS)		
		unfulfilled	mto	make-to-order	c)	Genetic Algorithm (GA)	g)	Petrie-Net (P)	j)	Threshold Accepting (TA)
	?	unspecified			d)	Hybrid GA (HGA)	h)	Particle Swarm (PS)		

TABLE VII
ELEMENTS OF OBJECTIVES IN RCPS RESEARCH

	earliness		tardiness		workload		make-span		inventory / WIP		cash-flow
	t.	m.	t.	m.	t.	m.	t.	m.	t.	m.	m.
[66] (1993)		✓		✓							✓
[67] (1994)			✓		✓		✓		✓		✓
[68] (1995)							✓				
[38] (1996)				✓							✓
[60] (1996)			✓				✓				
[58] (1997)					✓		✓				
[57] (1999)			✓								
[69] (2000)							✓				
[70] (2000)			✓								
[71] (2000)							✓				
[72] (2000)			✓				✓				
[73] (2001)							✓				
[74] (2002)		✓		✓			✓				
[75] (2002)							✓				
[76] (2003)							✓				
[77] (2004)							✓				
[78] (2007)											✓
[79] (2007)							✓				
[80] (2007)							✓				
[81] (2008)							✓				
[82] (2009)							✓				
[83] (2008)											
[84] (2010)							✓				
[85] (2010)							✓				
[86] (2006)							✓				
[87] (2010)			✓								
[88](2013)			✓								
[89] (2014)	✓						✓				
[90] (2015)							✓				
[*] (2015)				✓		✓		✓		✓	
Legend	t:		time-based		m:		monetary				

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