A pragmatic optimization-based approach for analysis and configuration of a reconfigurable multi-product assembly line in the automotive industry

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Abstract

Increasing product variety and fluctuating demand have led to the need of assembly systems that can adapt to multiple different products as the return of investment for dedicated assembly lines is more and more difficult to achieve. In response to this challenge, the paradigm of reconfigurable assembly systems has emerged. However, configuring and optimizing these systems still pose challenges in the industry. This paper proposes a new simple optimization approach for the configuration analysis and optimization of a reconfigurable multi-product assembly system in the automotive industry, using configuration selection, task allocation, and sequencing. Its effectiveness is validated throughout three real industrial study cases in the automotive supplier industry.

Keywords Assembly system configuration · Task-resource allocation · Sequencing · Mixed Integer Linear Programming · Product variety

1 Introduction

1.1 Global context

Industrial manufacturing companies are today evolving under multiple constraints within a field of tension. On one hand, the trend towards more and more product variety is still ongoing. On the other hand, the vulnerability of the globalized economy has been outlined by the significant impact of unpredictable diseases and emerging geopolitical crises on manufacturing firms. In addition to production shutdowns, ever increasing production cost due to inflation and the even more volatile market demand represent nowadays strong industrial challenges. Controlling investments in new production equipment has become crucial as the return of investment becomes more difficult to obtain. A lever to face this challenge is to establish a new production system for a product family instead of a single product [1]. This approach not only extends the system's lifespan but also allows for the absorption of demand fluctuations through adjustments of the product mix. Furthermore, the optimization of those multi-product production systems plays an important role as it allows for example to enhance its configuration and to improve the cycle time.

The present article aims at contributing to the implementation of adaptable, reconfigurable production systems in industry. The research lies in the field of applied research. The results and conclusions presented in the article are based on an industrial research project (project type RDI: Research Development Innovation) conducted by mixed teams comprising academic researchers and industrial engineers, in collaboration between Arts et Métiers and its company in the automotive sector.

Figure 1 illustrates the overall scope of the RDI project which is divided into three parts. This article focuses on the second part, i.e., providing a new optimization approach, validated throughout industrial case studies in the automotive supplier industry, to contribute to the deployment of multi-product assembly systems in industry.

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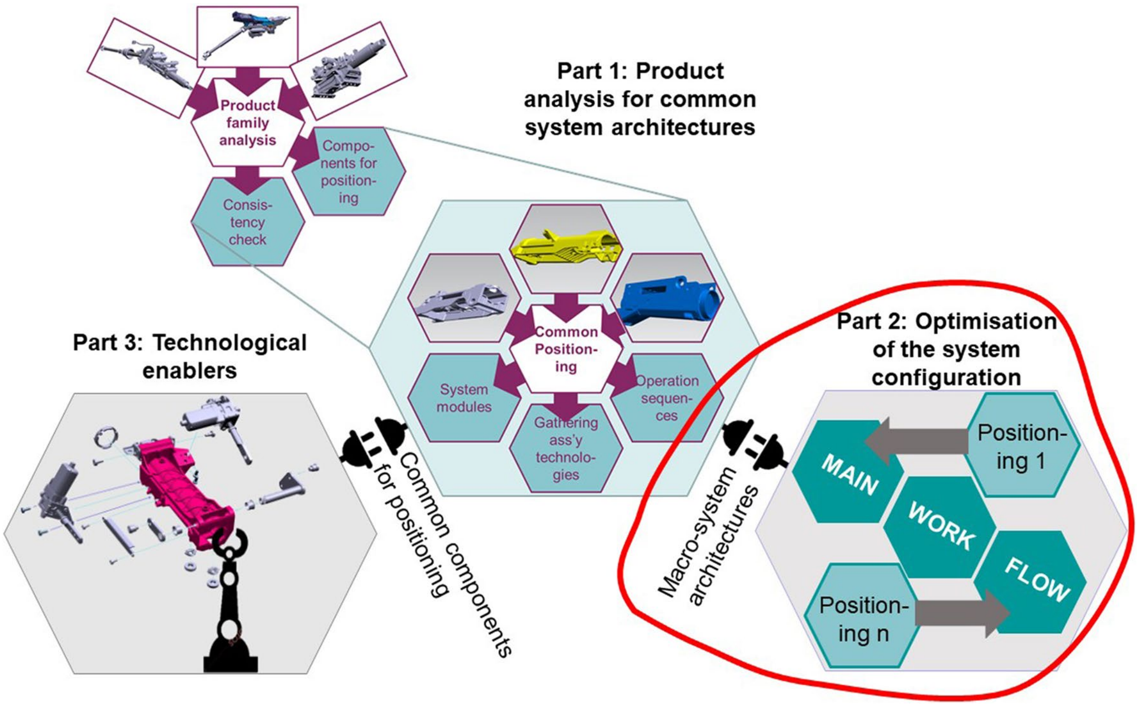


Fig. 1 Scope of the RDI project and scope of the article

1.2 Identified industrial needs and research question

The presented research work is driven by industrial needs. In the case of multi-product assembly systems, the system designer is confronted with several questions. Given a predefined product family, the main questions are the following:

i. Which assembly system modules (with a module being a resource) are to be selected in the assembly system architecture?
ii. Which tasks (with a task being an assembly operation) are realized on each module?
iii. Which sequences are to be chosen for each task (= assembly operation) on each resource (= assembly system modules)?
iv. Which sequences are to be chosen between these resources?

These four questions are interdependent: module choice (i.e., resource selection) impacts the tasks which are feasible on each resource and eventually the permissible task sequences. The task allocation has an impact on the task sequences for each resource. Fixing at first the overall sequence initially can influence both the selection of resources and the possible task sequences. All those interdependencies are illustrated in Fig. 2. The difficulty of assembly system design and configuration in automotive industry is also underlined from an academic perspective in [2], emphasizing the difficulty to determine optimum configurations supported by adapted decision-making tools.

The challenge is to find the optimal trade-off between those four questions. A separated approach of addressing these problems risks missing a global optimum because the isolated optimization of a single factor may constraint the solution space of the other factors to sub-optimal solutions. For these reasons, the proposed optimization approach should simultaneously handle resource selection, task and resource allocation, and sequencing. In order to detail the positioning of the presented approach in relation to the main terms used in optimization literature, we provide the scope within task-resource allocation, layout planning, scheduling, and process planning:

- Task-resource allocation: Main topic of the paper
- Layout planning: Macro layouts may be evaluated by the model, but in the used study cases, the working hypotheses have been used according to the industrial problem and a given layout is treated
- Scheduling: Task scheduling is not conducted in detailed manner (no detailed start and end time for each task). Instead, we evaluate the global time and cost of a resource is evaluated in a worst-case evaluation. Task

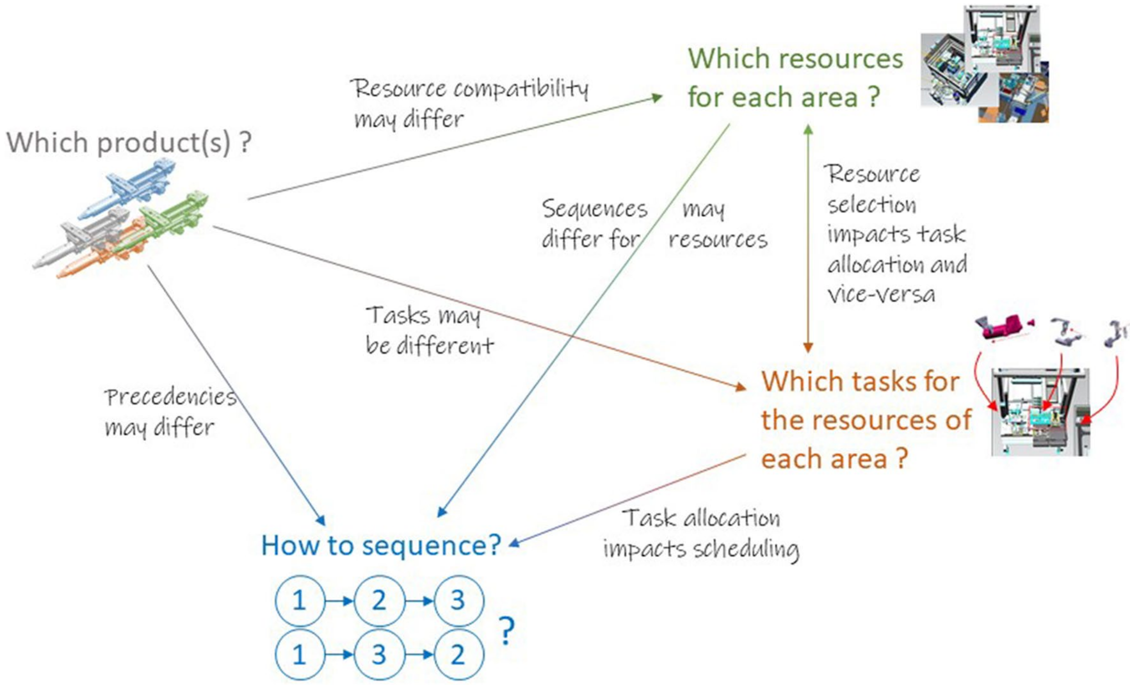


Fig. 2 Industrial problematics

sequencing is considered only to evaluate the global sequence duration and cost for each resource in order to minimize them.

- Process planning: There is flexibility in process planning, which in turn allows flexibility in task-resource allocation. However, process planning optimization itself is not in the central focus of the approach.

The structure of the paper is as follows: Sect. 2 details related literature on reconfiguration in general and on approaches to determine configurations in detail. The developed model is presented in Sect. 3, as well as the data structure and its implementation. The application of the developed approach to an industrial case study in the automotive industry is then described in Sect. 4. Finally, the conclusions and perspectives are presented in Sect. 5.

2 Literature review

The literature review is divided into two sections: A short review on reconfigurable manufacturing and assembly systems in general based on review papers to underline the need and the importance of configuration selection and optimization approaches and a detailed review on existing optimization approaches with an analysis of their applicability to the industrial problem.

2.1 Literature on RAS and RMS

The use of reconfigurable systems for assembly and manufacturing has been introduced as solution to cope with product diversity. A such system is outset to handle a set of products gathered into a product family [3]. In recent work, there have been more detailed insights into understanding which impact of the reconfigurable manufacturing system (RMS) core characteristics and when they are important during the RMS life-cycle [4]. Examples of investigations into reconfigurable assembly applied to the automotive sector exist: the advantage of reconfigurable assembly line configurations by using mobile robots instead of static fixed robots is emphasized in [5]. Rösiö et al. [6] presents a reconfigurability assessment method in the automotive industry and [7] evaluates flexibility levers in an automotive mixed-model assembly line. Through their early literature review on reconfigurable manufacturing and assembly systems, Bi et al. state that further explorations were needed to design a configurations for RMS [8], for example as presented in [9, 10] which describe decision-making processes for robotized automotive assembly line configurations and the use of search algorithms to derive new configurations. However, there has been a lack of modelling and optimization tools for the configuration design such systems [11]. Koren et al. [12], in their recent review, identify one principle for reconfigurable systems: the use of task allocation and operation reconfiguration to maximize system productivity. Finally,

[13] locate the optimization of system configuration in RMS research stream 4 on applied research. They emphasize that configuration selection is crucial for the management of RMS and the use of optimization models, among others, is a widely used approach in research. In the following subsection, a more detailed review of optimization approaches for configuration selection is presented.

2.2 Literature on configuration approaches of RAS and RMS

Recent reviews of optimization approaches for reconfigurable systems have been carried out by [14] and [15]. The former review shows a wide range of optimization approaches in literature, concerning different domains such as process planning, layout design, and reconfigurability which is subdivided into configuration selection, cellular systems, machine selection, planning, and scheduling. The latter review divides the literature into three main areas: the choice of objective functions, the selection of optimization method (exact, heuristic, etc.), and the classification of the optimization problem (design, process planning, etc.). By mapping the described industrial problems with the aforementioned subdivision of RMS optimization problems, the following characteristics of the optimization approach have been identified:

- The architecture is fixed as serial flow line with multiple products.
- The objective function falls within in the domain of *multi-objective optimization* considering cost and production time. Cost encompasses investment and operating cost, while production time considers the completion time of each workstation.
- The problem classification falls into in two areas: *flow line configuration selection* and *planning and scheduling*. Task sequencing must also be considered in the latter.

An exact method for to find the global optimum is preferred to respond to the industrial partner's requirements. This literature review does not pretend to be exhaustive given the huge amount of operations research literature published during the last decade. Instead, it aims to provide an overview of the approaches developed in the context of reconfigurable systems and flow line configuration selection. The examined literature has been classified using the categories mentioned above, and the results are presented in Table 1 (sorted alphabetically by the first author).

Most of the approaches focus on manufacturing systems, which consider that the system is composed of either flexible manufacturing cells able to conduct multiple processes or reconfigurable machine tools (RMT). Fewer approaches exist considering assembly systems.

On the machine level, [17] developed a multi-objective approach for the configuration selection of a manufacturing system and its RMT for multi-product application. The work has been completed by an approach of configuration selection of machine modules considering modularity [19]. Bensmaine et al. [20] also propose an approach for machine selection based on tool configurations considering time and cost, while [22] consider maximizing the throughput and minimizing energy consumption. Another triple-objective approach is presented in [46], who consider cost, line balance, and machine precision of RMT. Goyal and Jain [30] propose a four-objective-approach for RMT configuration selection considering cost, machine utilization, operational capacity, and convertibility. Finally, [16] include another four objectives for RMT configuration selection: cost, reconfigurability, operation capacity, and reliability.

A planning approach in regard of available machine tools considering time and flexibility is proposed in [18]. Touzout and Benyoucef [44] and [34] developed an approach for planning and scheduling in an RMT system considering time, energy consumption, and cost. In addition, [33] consider time, cost, and sustainability by regarding hazardous waste.

Bridging configuration selection at both the machine and the system level in RMS, [49] propose a method for both by considering cost. The initial method using the genetic algorithm (GA) has been extended by tabu search [50, 51].

On the system configuration selection level, minimization of capital cost based approaches using graph theory [23, 24] and GA [25, 26] have been proposed. Saxena and Jain [43] consider the RMS evolutions in an evolutive configuration selection adding the aspect of machine availability. Maniraj et al. [39] propose minimizing the cost of machining RMS by using optimal process plans. The machining cell formation for system configuration considering grouping efficiency has been evaluated by [29]. A method considering evolving product families and aiming at optimizing assembly system life cycles for the entire system lifetime is presented in [21]. Finally, [45] propose a configuration selection by considering costs and buffer allocation for the machine selection, and [36] present a generic approach to task allocation to services under evaluation of cost, quality, and time.

Considering both, system configuration selection and scheduling, [42] present a very detailed cost analysis for an assembly system, in regard of available assembly tools. In [27], capital and reconfiguration cost, as well as tardiness, are considered.

Planning and scheduling of assembly and manufacturing systems is addressed, for example, by [47] in terms of cost, time, and balancing; by [35] considering due date, balancing, and reconfiguration cost; and by [40] evaluating completion time and energy consumption. A special case is the

Table 1 Synthesis of the literature review

References	Objective function			Classification		Method		Considered item			System type	Scope	Industrial case study
	C	T	O	CS	P&S	Exact	Heuristic	WS	MHS	MT			
[16]	X		R, Re, Oc	X			NSGA-II			X	Man	MP	N
[17]	X		Ro	X			NSGA-II	X		X	Man	MP	N
[18]		X	F		X		NSGA-II	X		X	Man	SP	N
[19]	X	X	M	X			AMOSA			X	Man	MP	N
[20]	X	X		X			NSGA-II			X	Man	SP	N
[21]	X			X		NLIP	GA	X			Ass	MP	N
[22]		X	E	X	X	MILP (CPLEX)			X	X	Man	MP	Y
[23, 24]	X			X		CKSP		X			Man	SP	Y
[25, 26]	X			X			GA	X			Man	MP	N
[27]	X		Ta	X	X		NSGA-II	X			Man	MP	N
[28]	X		Ta	X	X		MOPSO	X			Man	MP	N
[29]			Eff	X		BIP (CPLEX)		X			Man	MP	N
[30]	X		R, Oc, U	X			MOPSO	X		X	Man	SP	N
[31, 32]		X	Co		X		PSO	X			Ass	SP	N
[33]	X	X	Hl		X	WGP		X			Man	SP	N
[34]	X	X	E		X	MNILP		X			Man	SP	N
[35]	X	X	Ba		X		MOSOMA	X			Ass	MP	N
[36]	X	X	Q		X		ACO, NSGA-II	X			-	-	N
[37]	X	X	Q		X		ACO	(X)			Man	SP	N
[38]	X				X	MILP (CPLEX)		(X)	(X)		Log	MP	N
[39]	X				X		ACO			X	Man	SP	N
[40]		X	E		X	(CPLEX)	GA, PSO	X		X	Man/Ass	MP	N
[41]			Ba, Red		X	NLIP (CPLEX)		X			Man/Ass	SP	N
[42]	X			X	X	(CPLEX)	MBFA-GA	X		X	Ass	MP	N
[43]	X		Av	X			AIS	X			Man	MP	N
[44]	X	X	E		X	(I-MOILP)	NSGA-II, AMOSA	X			Man	SP	N
[45]	X			X			NSGA-II, SA, DCM	X			Man/Ass	SP	N
[46]	X		Ba, Mp	X			GA			X	Man	SP	N
[47]	X	X	Ba		X		MOHPSO	X			Ass	MP	N
[48]	X		S		X	MILP	LR	X			Man	MP	N
[49–51]	X			X			GA, TS	X		X	Man	MP	N

Column titles: *C* cost, *T* time, *O* other, *CS* configuration selection, *P&S* planning and scheduling, *WS* workstation, *MHS* material handling system, *MT* manufacturing tool; objective functions: *E* energy, *Eff* efficiency, *F* flexibility, *M* modularity, *Ta* tardiness, *B* benefits, *Q* quality, *R* reconfigurability, *Re* reliability, *Oc* operation capacity, *Ro* robustness, *Red* redundancy, *Ba* balancing, *Co* component related, *Mp* machine precision, *Av* availability, *Hl* hazardous liquids, *S* sustainability, utilization; methods: *SA* simulated annealing, *DCM* decomposition-coordination method, *BIP* binary integer programming, *PSO* particle swarm optimization, *NLIP* non-linear integer programming, *MILP* mixed-integer linear programming, *CKSP* constraint k-shortest path, *NSGA-II* = non-dominated sorting genetic algorithm II, *MOSOMA* multi-objective self-organizing migrating algorithm, *AIS* artificial immune system, *TS* tabu search, *ACO* ant colony optimization, *WGP* weighted goal programming, *LR* Lagrangian relaxation; system type, scope, industrial case study: *Ass* assembly, *Man* manufacturing, *Log* logistics, *MP* multiple product, *SP* single product, *Y* yes, *N* no

optimization of redundancy to compensate resource failure in automated flow-lines through task re-allocation as presented in [41], completed by simulation based evaluation [52]. More specific cases are addressed by [37] who consider the allocation of tasks to manufacturers regarding delay, cost, and quality, by [38] who optimize costs in a logistics-oriented problem, and by [31, 32] who develop a disassembly optimization approach considering idle time, the removal of hazardous components, and the component value. Finally, [48] propose an approach that strongly focuses on sustainability considering its social and environmental aspect in addition to cost.

In conclusion, there is a majority of literature on manufacturing and less literature on assembly. However, an assembly system does not have the same characteristics as a manufacturing system: The complexity of manufacturing system optimization is linked to the combinatorial complexity of routing possibilities and machine configurations. Process precedencies for feature generation and part geometry are less complex. In assembly, complexity linked to possible routing is lower but in an industrial assembly, task precedencies are complex and offer different sequencing possibilities. These also have strong compatibility constraints with the resources as the product geometry becomes more and more complex during the assembly process. There is therefore a lack of literature addressing the optimization of assembly systems. Also, few approaches simultaneously address configuration selection and planning. However, a sequenced method risks to find only local optima. Another shortcoming is the very small number of real industrial case studies, most of the articles using educational illustrations or theoretical benchmarks. This need for practical applications, in particular for mixed-model sequencing has also been highlighted in the literature review conducted by [53]. And last, none of the examined approaches corresponded to all the aforementioned criteria defined based on the industrial problem. In consequence, a new mathematical model and an exact method are proposed in the following section.

3 Mathematical model, data structure and implementation

This section details the mathematical model, the data structure, assumptions for cost calculation, and the implementation. The aim of the mathematical model is to propose, at the system level, a multi-objective optimization model (considering both, cost, and time), that is capable of simultaneously conducting configuration selection through task-resource allocation and task sequencing on the resources.

3.1 Mathematical model

The presented problem has been formulated as a Mixed Integer Linear Programming (MILP) with the aim to obtain optimal solutions. The following subsections detail the indices, parameters, and variables, the objective function with its two objectives and the chosen normalization, and the set of constraints used in the model. For the entire industrial application, the hypothesis has been used that the time needed for material flow between the resources is always less than the time required for task execution. As consequence, the material flow is not in the scope of the optimization. The hypothesis has been validated with the industrial partner based on real production data.

3.1.1 Indices, parameters and variables

Seven indices are used throughout the mathematical model and nine parameters have been identified. Seven parameters are linked to the assembly modelling and two parameters are used to weight the two objectives in the objective function. Finally, six variables are defined (Table 2).

3.1.2 Objective functions and normalization

The proposed new mathematical model concerns multi-objective optimization. It involves the simultaneous optimization of two performance indicators which in this case are (i) cost and (ii) the cycle time of the assembly system. Those two objectives are likely to be contradictory and, therefore, the solution can be distributed along a Pareto front end representing a set of solutions which are the trade-off between the objectives. In consequence, the final goal of multi-objective optimization is to identify the entire set of possible solutions on the Pareto frontier.

The first objective function P1 aims at minimizing the overall cycle time of the assembly system for all selected products:

$$\boldsymbol{P}1 : MinT^{max} \tag{1}$$

The second objective function P2 aims at minimizing the sum of all costs linked to the production (production cost (€) + adjustment cost (€)).

$$\begin{aligned}\boldsymbol{P}2 : MinCT = &\sum_{n=1}^{N}\sum_{i=0}^{I}\sum_{k=1}^{K} Y_{ink} \cdot p_{ink} \cdot c_k \\ &+ \sum_{n=1}^{N}\sum_{i=0}^{I}\sum_{j\neq i}\sum_{k=1}^{K} X_{ijnk} \cdot a_{ijk} \cdot c_k\end{aligned} \tag{2}$$

Both objective functions are combined by using the method of the weighted sum, classified in the range of a priori Pareto methods by [54]. The relative weights being defined by the parameters α_1 and α_2.

$$\boldsymbol{P}(1+2) : Min\left(\alpha_1 \cdot P1 + \alpha_2 \cdot P2\right) forall \alpha_1 + \alpha_2 = 1(\alpha_1, \alpha_2 \geq 0) \tag{3}$$

The most current approach for multi-objective optimization is the weighted sum method [55] presented above. However, this method shows some difficulties to find a set of solutions which is distributed at the Pareto front end when each of the objectives has an interval of values which differs a lot from the other ones. For this reason, a normalization is proposed to balance the value intervals of each of the objectives [56].

$$\begin{aligned}\boldsymbol{P}(1+2) : Min\left(\alpha_1 \cdot \left(\frac{P1 - P1^*}{P1^*}\right) + \alpha_2 \cdot \left(\frac{P2 - P2^*}{P2^*}\right)\right), \\ \alpha_1 + \alpha_2 = 1(\alpha_1, \alpha_2 \geq 0)\end{aligned} \tag{4}$$

Table 2 Summary and description of indices, parameters and variables

	Name	Description
Indices	i, j:	Index of tasks $(0, 1 \dots I)$ where 0 and 1 are virtual tasks "start" and "finish" used for sequence definition on each resource but with other signification in the real assembly process
	k:	Index of all resources $(1 \dots K)$
	n:	Index of products in the chosen product family $(1 \dots N)$
	m :	Index of all resource types $(1 \dots M)$
	b_m :	Set of resources for resource type m
	l:	Index of interchangeable resource types that can be selected for the same place in the configuration $(1 \dots L)$
Parameters	e_{in}:	Assembly definition: 1, if task i must be realized to assemble product n, otherwise 0
	f_{ik}:	Task-resource compatibility: 1, if task i is compatible with resource k, otherwise 0
	p_{ink}:	Production time needed on resource k to fulfill task i
	c_k:	Production cost for resource k, expressed by time unit (seconds)
	b_{ij}:	Precedence: 1, if task i must be realized before task j may start, otherwise 0
	g_{ijk}:	Task-task compatibility: 1, if task i is compatible to precede task j on resource k, otherwise 0
	a_{ijk}:	Adjustment time if task i precedes task j on resource k
	α_1:	Weight for objective function 1, between 0 and 1
	α_2:	Weight for objective function 2, between 0 and 1
Decision variables	Z_k:	Resource selection: 1, if resource k is selected, otherwise 0
	Y_{ink}:	Task-resource allocation: 1, if task i of product n is realized on resource k, otherwise 0
	X_{ijnk}:	Task precedencies: 1, if task i of product n precedes task j of the same product on the resource k, otherwise 0
	CT:	Overall production cost for the selected products
	T_{nk}:	Cycle time of resource k for product n
	T^{Max}:	Cycle time of the entire assembly system considering all selected products and all chosen resources

3.1.3 Constraints

Nine constraint types are introduced in the following: The constraint of task allocation for all products (Eq. (5)) ensures that all required tasks i are realized for each product n:

$$\sum_{k=1}^{K} Y_{ink} = e_{in} \ \forall i \epsilon I/\{0,1\}, \ n \epsilon N Y_{ink} = 1 \ \forall i \epsilon \{0,1\}, \ n \epsilon N, \ k \epsilon K \tag{5}$$

The constraint for task-resource compatibility (Eq. (6)) verifies that task i of product n can be performed on resource:

$$Y_{ink} \leq f_{ik} \ \forall i \epsilon I, \ n \epsilon N, \ k \epsilon K \tag{6}$$

The resource allocation constraint (Eq. (7)) checks that at least one task i of a product n is assigned to each resource k:

$$Y_{ink} \leq Z_k \ \forall i \epsilon I, \ n \epsilon N, \ k \epsilon K \tag{7}$$

The resource type constraint (Eq. (8)) ensures that only one resource must be chosen from a list of available alternatives when the optimization approach needs to select from different available alternatives of a specific resource for the same tasks.

$$\sum_{\forall l \epsilon \{b_m\}} Z_l \leq 1 \ \forall m \tag{8}$$

The precedence constraint (Eq. (9)) verifies that the precedence of task i with task j on the same resource and for the same product is compatible to the task precedencies defined by parameter b_{ij}:

$$X_{ijnk} \leq b_{ij} \cdot \left(\frac{Y_{ink} + Y_{jnk}}{2} \right) \forall i \epsilon I, j \neq i, n \epsilon N, k \epsilon K \tag{9}$$

The task compatibility constraint (Eq. (10)) assures that the task i which precedes task j on the same resource and for the same product is consistent to the compatibility of tasks on the resources determined by parameter g_{ijk}:

$$X_{ijnk} \leq g_{ijk} \forall i \epsilon I, j \neq i, n \epsilon N, k \epsilon K \tag{10}$$

The sequence constraints (Eqs. (11), (12), and (13)) assure that there are no loops in the task sequences on the same resource:

$$X_{ijnk} + X_{jink} \leq \left(\frac{Y_{ink} + Y_{jnk}}{2} \right) \forall i \epsilon I, j \neq i, n \epsilon N, k \epsilon K \tag{11}$$

$$\sum_{j=1, j \neq i}^{I} X_{ijnk} = Y_{ink} \ \forall i \epsilon I/1, \ n \epsilon N, \ k \epsilon K \tag{12}$$

$$\sum_{j=0(/1),j\neq i}^{I} X_{jink} = Y_{ink} \ \forall i\epsilon I/0,\ n\epsilon N,\ k\epsilon K \tag{13}$$

The maximum time constraints calculate, for each resource, the time needed to complete the allocated tasks (Eq. (14)) and determine the time of the "slowest" resource as the maximum system time (cycle time) (Eq. (15)):

$$T_{1nk} = \sum_{i=1}^{I} Y_{ink} \cdot p_{ink} + \sum_{i=1}^{I} \sum_{j\neq i} X_{ijnk} \cdot a_{ijk} \forall n\epsilon N, k\epsilon K \tag{14}$$

$$T^{Max} \geq T_{1nk} \ \forall n\epsilon N,\ k\epsilon K \tag{15}$$

Finally, the variable domain constraint (Eq. (16)) determines the domain of each of the five concerned variables: binary for *X, Y, Z*, and positive for the times.

$$X_{ijnk}, Y_{ink}, Z_k \epsilon \{0,1\} \& T^{max}, T_{1nk} \geq 0 \ \forall i\epsilon I,\ j \neq i,\ n\epsilon N,\ k\epsilon K \tag{16}$$

3.2 Data structure

The input format of data into the optimization model is text files (.txt) with tabulation. For ergonomic reasons and to enhance communication with the industrial partner company, Excel files have been used for the data acquisition. The table content of these Excel files has then been transferred to the text files. The global structure of data acquisition is illustrated in Fig. 3. Assembly resource analysis and product analysis have been carried out by the industrial partner. Assembly precedencies have been defined conjoint by the research team and the industrial partner, as well as task compatibilities.

Optimization approaches are a very well-known topic in research, with plenty of methods are developed and investigated. However, their mathematical complexity introduces difficulties for a broad diffusion in industry. Additionally, calculation time, problem complexity, and size remain unclear. Only a very few papers provide real industrial application. In consequence, their application and comprehension encounter barriers on the industrial side. Therefore, a data acquisition table has been introduced in order to create a common interface between the industrial partner and the research group (Fig. 4). It has been developed collaboratively to enhance the comprehensibility of the approach and to be in a format which enables ergonomic and rapid data input on the industrial side. For the cost calculation, investment cost is obligatory, while cost per part per second would be helpful. As the latter has not been available for the present application, it has been calculated separately using the method presented in subsect. 3.3.

In addition to the data acquisition table, six distinct tables have been used to determine the values of the parameters. The structure of these tables is schematically illustrated in Fig. 5.

The values in the tables f_{ik}, e_{in}, and p_{ink} are deduced from the data acquisition table. The precedence table b_{ij} has been completed by using precedence graphs validated by the industrial paper. Even if the products are varying, their overall assembly task precedence structure is similar. The values in the table for task compatibility have been filled by using industrial information about tasks that cannot be placed on the same resource or that cannot be combined when using the overall precedence structure. The adaptation times have been estimated by the industrial partner for the resources on which adaptation could be technically possible.

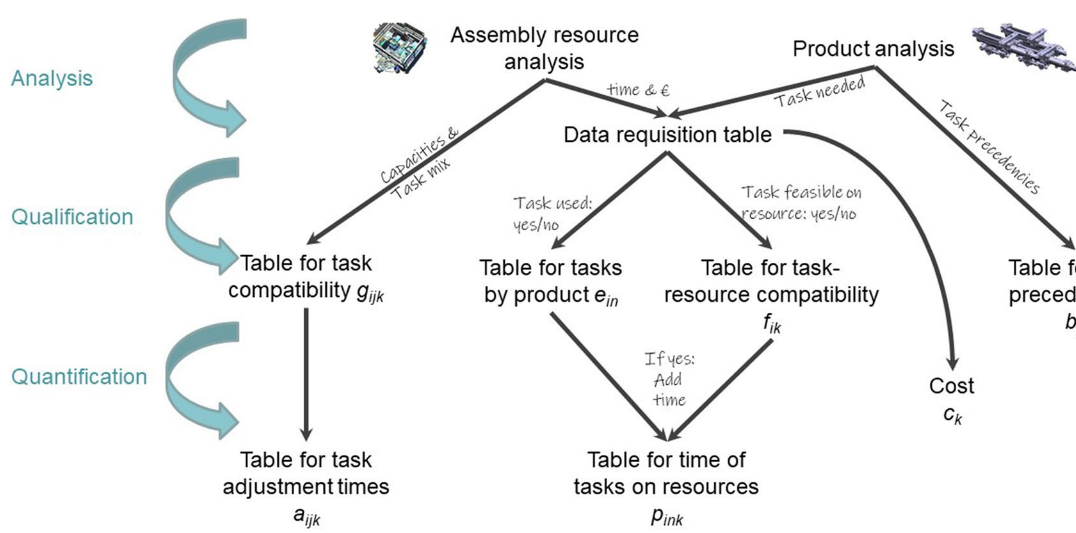


Fig. 3 Data structure and link between the tables

Data acquisition table (to be completed by the industrial company)

Task description				Cost		Times for resource 1			Times for resource …		
Task type	Operation ID	Illustra-tion	Task description	Investment cost	Cost/part/second	Operator time	Machine time	Global time	Operator time	Machine time	Global time
Joining,…	Op1	Photo	Text	…€	…ct/s	Time in seconds for operator or/and machine If resource is not used, put ∞		Agrégation of operator and machine time	Time in seconds for operator or/and machine If resource is not used, put ∞		Agrégation of operator and machine time
…	Op1			…€	…ct/s						
…	Op2			…€	…ct/s						
…	Op…			…€	…ct/s						

Fig. 4 Data acquisition table—common interface with the industrial company

Task identification for each product e_{in}

Task description	Task number	Product 1	Product n
Start	0	1	1
End	1	1	1
Task 1	2	1 if task is used 0 else	
Task i	i+1		

Time of tasks on resources for each product p_{ink}

Task description	Task number	Resource 1	Resource k
Start	0	0	0
End	1	0	0
Task 1	2	Time in [s] if compatible 1000 else	
Task i	i+1		

Task-resource compatibility f_{ik}

Task description	Task number	Resource 1	Resource k
Start	0	1	1
End	1	1	1
Task 1	2	1 if resource can be used 0 else	
Task i	i+1		

Task precedencies b_{ij}

Task description and numbers		Start	End	Task 1	Task j
		0	1	2	j+1
Start	0	0	1	1	1
End	1	0	0	0	0
Task 1	2	0	1	0	
Task i	i+1	0	1		0

1 if task *i* before task *j*
0 else

Task compatibility for each resource g_{ijk}

Task description and numbers		Start	End	Task 1	Task j
		0	1	2	j+1
Start	0	0	1	1	1
End	1	1	0	1	1
Task 1	2	1	1	0	
Task i	i+1	1	1		0

Task adjustment time for each resource a_{ijk}

Task description and numbers		Start	End	Task 1	Task j
		0	1	2	j+1
Start	0	0	0	0	0
End	1	0	0	0	0
Task 1	2	0	0	0	
Task i	i+1	0	0		0

Adjustment time from *i* to *j*

1 if task *i* is compatible with task *j* on the same resource
0 else

Fig. 5 Table structure for data collection and formalization

3.3 Cost calculation

The optimization model relies on cost as the unit of money per part per second for each resource. If this data is available, no further calculation has to be done. It can be used directly in the cost table c_k. In the present case, this data was unavailable, so two types of costs have been considered for its calculation: the cost linked to the investment, and the cost linked to the operators. Energy cost has not been considered as—for the present case—it can be assumed that the difference in energy consumption between the different solutions is almost constant and of minor importance relative to the investment and operator costs. Therefore, it is considered to have no impact on the optimization. This hypothesis has been validated by the industrial partner.

The total resource investment cost is divided by the years of depreciation to calculate its yearly ratio. The operator cost (total hourly employment cost) is multiplied by the yearly assembly system opening time in hours and by the number of operators needed for the resource (decimal operator numbers are possible if the resource shares an operator with another one). The resource cycle time is multiplied by the OEE (overall equipment effectiveness, a percentage between 0 and 100) to have its real cycle time in seconds. The yearly assembly system opening time (in seconds) is then divided by the real cycle time to get the annual production on the resource. The sum of the yearly operator cost and the yearly ratio of the investment is divided by the annual production to obtain a resource cost by part. Finally, this cost is divided by the real resource cycle time to determine the resource cost per part per second needed for the optimization model.

3.4 Resolution method and implementation

As mentioned before, the mathematical problem has been formulated as Mixed Integer Linear Programming (MILP). After discussions with the industrial partner, the commercial solver *IBM ILOG CPLEX Optimization Studio*, version 12.8, has been chosen as it is available for industries and adapted to the size of the problem. This solver is based on cutting plane methods which are used together with branch and bound algorithms [57]. It is well-suited to provide optimal solutions for integer linear programming problems, such as the one presented in this paper. By utilizing a function within the CPLEX solver, we can determine the optimality status of the acquired solution (feasible, infeasible, optimal, non-optimal, …). This optimality status has been indicated for each of the solutions presented in the following section. The application in this paper has been realized using the academic version.

To import and exploit the raw data presented in the previous subsection to the CPLEX solver, two complementary modules have been programmed, being compatible with the solver: one module to read the data and to format it to fit into the solver and a second module to decode the results and to write them into a save file in text format. Those complementary modules have been implemented in Java programming language using *Eclipse IDE for Java Developers*.

The input data must be inserted into a text file which contains all the tables indicated in Fig. 5. The function "read data" has been developed and implemented in Java, as well as the mathematical model. Then, the model is solved by the CPLEX module. Finally, the results are decoded and written in an output text file. The decoding and writing modules have also been implemented in Java.

All case studies have been run with Intel® Core™i5-8400H CPU@2.50 GHz, 4 cores, 8 processors, and 16 of GB RAM, running on Windows 11. Depending on the complexity of the case study, the calculation time has never exceeded 8 s and usually falls between 3 and 5 s.

4 Case study

During the research project, a real automotive assembly production line, whose global architecture had been determined in previous research work, has been analyzed and optimized using a newly proposed mathematical model. Three case studies have been conducted, each increasing in the problem complexity of the considered assembly line. The first case analyses the existing system in a frozen configuration (one product, no freedom in task-resource allocation, and sequencing). Its primary aim is to compare the optimization results obtained by the new mathematical model with the performance of the real system in order to validate the implementation. The second case optimizes and evaluates a task-resource allocation and sequencing problem for some of the tasks which can be allocated to different resources within the same system. Finally, the third case evaluates the task-resource allocation problem involving two different products on the same production line.

The assembly system architecture is illustrated in Fig. 6. It represents the first multi-product assembly line on the production site of the industrial partner. The scope of the different study cases is highlighted. As the detailed design of the production line is confidential, only its architecture with the main assembly processes can be displayed. It should be noted that the screwing workstations S1 to S3 have a particular design with a manual and an automated part. The tasks of both parts are performed in parallel, unlike the other resources where tasks are serial. An exchange device is used to connect both parts, and when products are exchanged, both parts (operator and robot) have to wait. This is indicated by "idle time" in the study case descriptions.

For the connection between the preassembly areas and the main production line, after discussion with the industrial partner, the hypothesis has been used that the parts from the preassembly area are always available on the main production line. In reality, this availability is achieved with a small intermediate stock on each resource of the main line. Therefore, the completion time of the resources in the preparation areas does not impact the system cycle time.

The product type which is assembled on the production system is illustrated in Fig. 7. Each subassembly is composed of a minimum of five or more parts, and the products have a total part count of 40–50 parts to assemble. The products used in the study cases represent the most complex ones in the company's portfolio. Thus, their use in the optimization approach represents the "worst case" in terms of task number, task variety, and component number. However, the actual products used for the case study

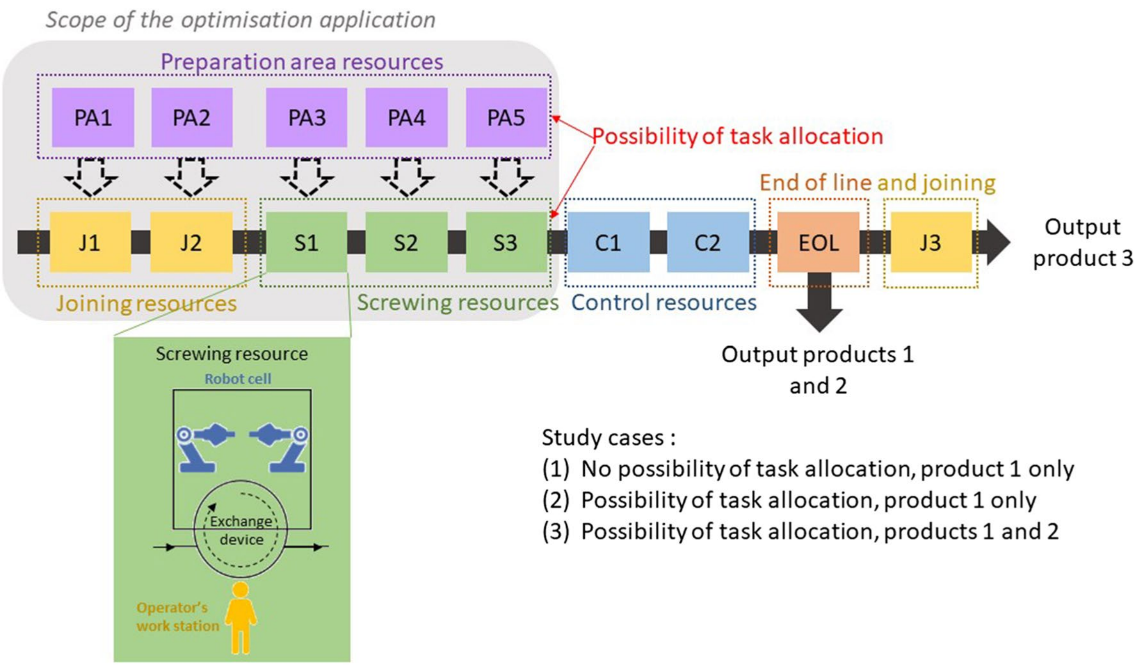


Fig. 6 Assembly system architecture

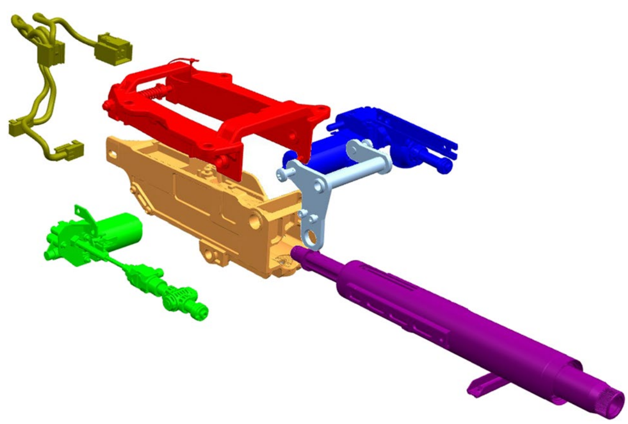


Fig. 7 Main subassemblies of steering column assembly

cannot be displayed due to confidentiality reasons. The presented system can be considered as reconfigurable because it is outset to assemble a product family of three different products. The reconfiguration concerns assembly tools and fixtures. However, the lot size for production is at least equal to one week of production, so the reconfiguration is not done instantly from one assembled product to another one, but carried out at the end of each production cycle.

4.1 Study case 1—existing system: one product with predetermined tasks, resources, and sequencing

As mentioned above, the first study case analyses the existing system configuration. The aim is at the one hand to validate the mathematical model by comparison of the desired performance with the calculated one and on the other hand to point at critical points of the existing configuration by identifying the bottlenecks. The data input consists of the measured time for each task. In addition, all results have been translated to relative values to avoid to publish sensitive industrial data. The targeted cycle time for the system is set equal to 100%. Since the system already exists, the mathematical model has only been used with the objective of time reduction in order to check if the assembly system cycle time and the resource completion times are in coherence with the industrial reality. Therefore, the coefficient α_1 has been set to 1 and α_2 to 0. The results of this first study case are illustrated in Fig. 8. The slowest resources in the preparation area and the main line are highlighted in red bold letters. The global performance of each resource compared to the targeted cycle time is indicated in percent. For each resource, the tasks performed on it are detailed, indicating their relative completion time (percentage of the total completion time of the resource). In consequence, the sum of the percentages of each task for the same resource is equal to 100%. The completion times for the manual part and the automated part in the screwing stations S1 to S3 are

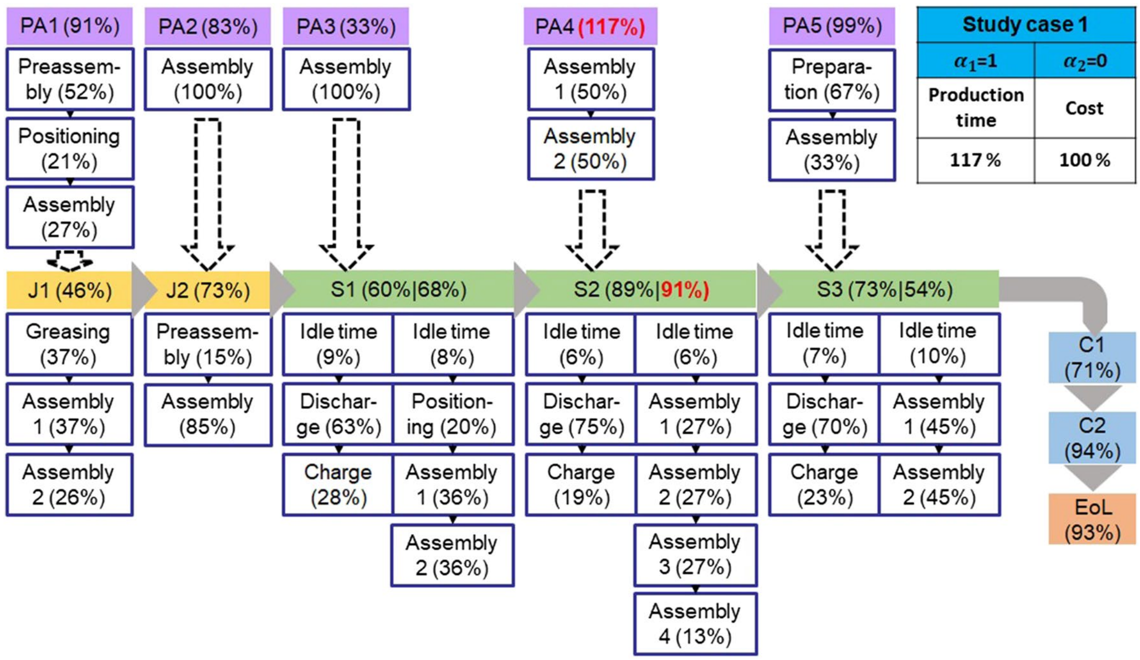


Fig. 8 Result of study case 1

given separately, with the manual part first and then the automated part.

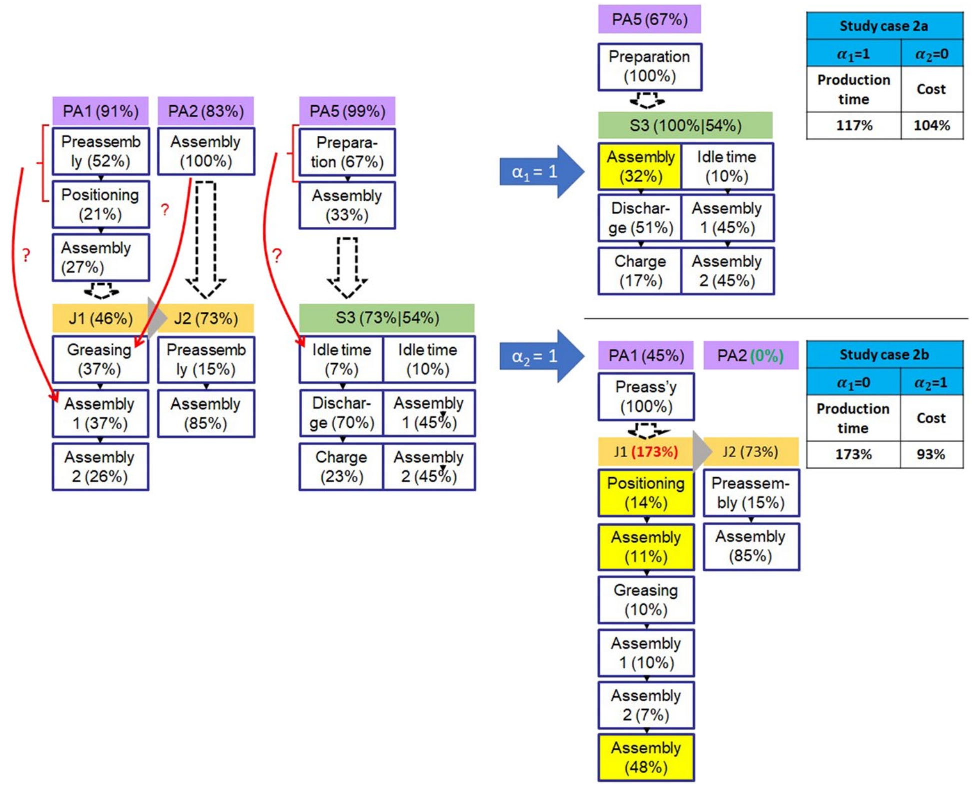
Two conclusions can be taken out of this first study case. Concerning the mathematical model, it has been proven that the mathematical model obtains realistic results which are consistent to the industrial reality. Concerning the assembly system, it has been emphasized that the bottleneck is situated in screwing section of the system, particularly in the automated part of screwing station S2. Nevertheless, resource S2 still meets the system cycle time objective as it is at 91% of the targeted time. Furthermore, a potential problem has been identified in the preassembly area as resource PA4 operates on 117% of the aimed cycle time. Even if the output of the preparation area is decorrelated from the main assembly line, it means that station PA4 has to be work longer (begin earlier or finish later) than the other stations in the system. Feedback and discussion with the industrial partner concluded that the assembly processes of this resource will be adapted to fit into the aimed cycle time. At the end of the main line, the control resources and the end of line (EoL) station have been added, even if they are not object to the optimization scope, to provide an overview of the entire system. As the analyzed product does not need resource J3, this resource is not displayed.

4.2 Analysis of optimization strategy of the existing system (one product with a degree of freedom to allocate some tasks)

Two questions emerged based on the first study case. In regard of the medium occupation time of resource S3, the first idea is to integrate the tasks of PA5 to it. In this way, the resource number of the system and the non-productive time of resource S3 could be reduced. The integration of the assembly task to S3 is conform to the precedence constraints. The second question is to study if the tasks of PA1 and PA2 can be integrated to J1 as J1 is only productive 46% of the cycle time. One may suggest to analyze also the integration of PA3 to S1; however, it is not possible due to technical incompatibilities.

The result of the second study case is illustrated in Fig. 9. To enhance the readability, only the concerned resources are displayed. The result indicates that the integration of preparation area tasks to the main line brings no optimization in regard of the two objective functions cost and time. In addition, the two solutions are contradictory. Study case 2a shows that the integration of only one of the two tasks of PA5 to S3 is possible (the tasks have to be allocated to the manual part as they cannot be realized technically in the automated part). There is no impact on the overall system cycle time as the concerned resources are no bottleneck and the proposed solution increases slightly the cost in regard of study case 1. Study case 2b shows that the integration of some of the tasks form PA1 and PA2 to J1 could improve the cost performance in comparison to study case 1. Resource PA2 is no longer needed in the assembly system. However, J1 becomes new bottleneck and increases the system cycle time in a considerable way. A double station would be needed to compensate which neutralizes the better cost performance. As 2a is increasing cost, and 2b is increasing time it is evident that the solutions cannot exist at the same time. To sum up, the second study case has put into evidence that there is no performance improvement for the system (in

Fig. 9 Result of study case 2



regard of the objective functions) by adding preparation area tasks to the main line resources.

4.3 Optimization of the global system configuration for two products

The last case study concerns the optimization of the assembly line for two products (product 1 and 2, leaving the assembly line after the EoL station). The assembly system cycle time for both products is the maximum cycle time comparing the individual cycle times of each product. The aim of this study case is to analyses the entire perimeter of possible system configurations which improve either the cycle time or the production cost by leaving the freedom to the optimization tool to modify task allocation to the assembly stations. The possibilities of task allocation are

Table 3 Results of multi-product optimization as function of alpha1 and alpha 2

α_1 (time)	α_2 (cost)	Total cost	Total Time	Detailed times				Detailed cost	
				Prod 1 PA	Prod 1 ML	Prod 2 PA	Prod 2 ML	Prod 1	Prod 2
1	0	107%	117%	117%	91%	117%	115%	100%	113%
0.9	0.1	105%	117%	117%	92%	117%	115%	99%	110%
0.8	*0.2*	*unchanged*		*unchanged*				*unchanged*	
0.7	*0.3*								
0.6	*0.4*								
0.5	*0.5*								
0.4	*0.6*								
0.3	*0.7*								
0.2	*0.8*								
0.1	0.9	102%	129%	117%	129%	117%	129%	97%	107%
0.07	0.93	101%	154%	117%	154%	117%	154%	96%	106%
0	1	100%	176%	117%	176%	117%	176%	95%	105%

Column titles: *PA* preparation area, *ML* main line, *Prod 1* product 1, *Prod 2* product 2 only constraint by task precedencies and task-resource compatibilities. The result of the third study case is displayed in Table 3. The first column indicates the values for weighting the objective functions of cost and time. The second column indicates the total system performance that means the maximum time of both products as "total time" and the sum of the cost as "total cost". At last, the detailed times (for each product and separated in main line and preparation area) and the detailed costs (for each product).

Changes in system performance occur only for extreme values of α_1 and α_2. A total of 100% of cycle time represent still the aimed system cycle time and 100% cost the cost of the configuration for product 1 as presented in study case 1. Comparing the detailed values of product 1 and product 2, it is interesting to see that the tasks of the preparation area have never been changed, even if the optimization program had the possibility to re-allocate them to the main line. It means that also in the case of two products, there is no interest in moving tasks from the preparation are to the main line. It becomes also evident that product 2 exceeds in every configuration the aimed cycle time in the preparation area and the main line (Fig. 10).

As shown in Fig. 1, the economy of cost impacts significantly the cycle time. A small cost improvement of 5% increases the cycle time 60%. The other way around, cycle time reduction does not heavily impact cost. Two results of the optimization are illustrated in Figs. 11 and 12.

Figure 11 shows the configurations for product 1 and product 2 if only cycle time is considered for optimization. The differences between the two products are highlighted with red boxes. It becomes evident that product 2 needs in general more time in the main line tasks and in the preparation area PA3, whereas it needs less time than product 1 in PA5 and EoL. These differences in task completion time are caused by differences in the product design (bearings, customer interfaces, accessories) which change the nature of the task. When putting the cursor on the optimization of production cost, it can be seen that the only changes which are done concern the allocation of tasks of the preparation areas PA1 and PA2 to the joining station J1 (highlighted in yellow in Fig. 12). This leads to the elimination of PA2 which justifies the cost reduction. The optimization results for intermediate values of α_1 and α_2 only change the number of tasks which are shifted from PA1 and PA2 to J1.

The result of the multi-product optimization shows that there is only very little optimization potential of the system configuration. When considering both products, the resources have a very good occupation rate. Therefore, the optimization analysis confirms that the configuration choice is pertinent for the present system. The proposal of allocating preparation area tasks to the main line have been discussed with the industrial partner. After a detailed analysis, it has been decided that the solution impacts too much the cycle time and that the system becomes too unbalanced.

To conclude the third study case, through the optimization approach the industrial partner has been comforted in the system configuration choices made for the first multi-product assembly line.

5 Conclusion and perspectives

The present paper aims to propose an optimization approach for the performance analysis and optimization of a reconfigurable multi-product assembly line. To achieve this, the need for a new mathematical model considering simultaneously configuration selection and task allocation with sequencing has been identified. It takes into account the assembly task precedencies and compatibilities, as well as assembly time and cost for each resource and for each product. The CPLEX solver has been chosen as it provides proven optimal solutions for Mixed Integer Linear Programming, is available to the industrial partner, and it fits to the problem size. The developed approach has been validated through

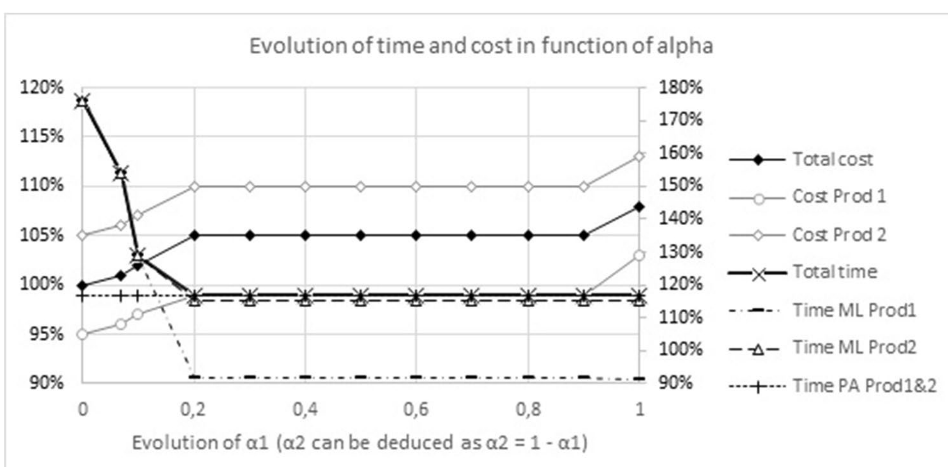


Fig. 10 Evolution of time and cost for product 1 and 2

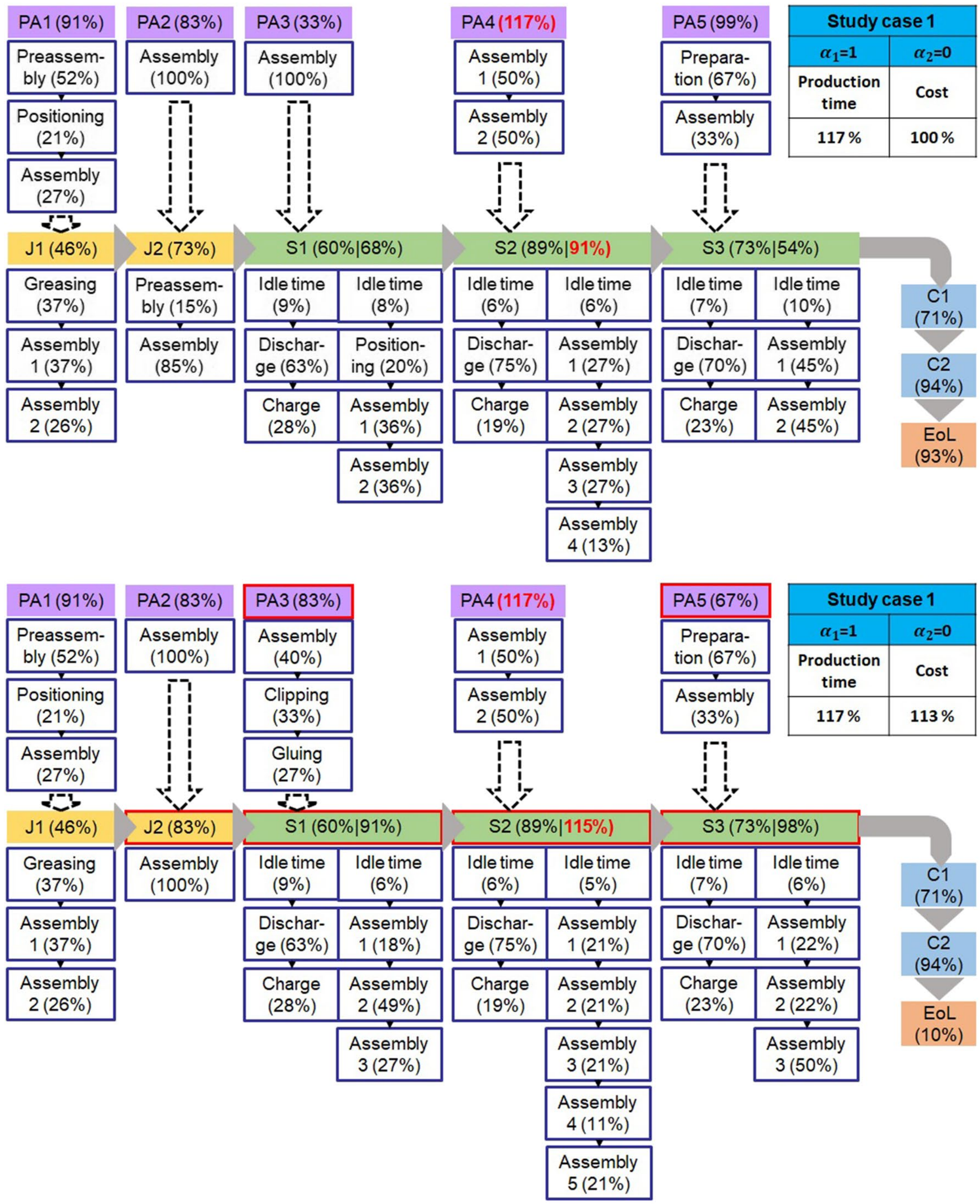
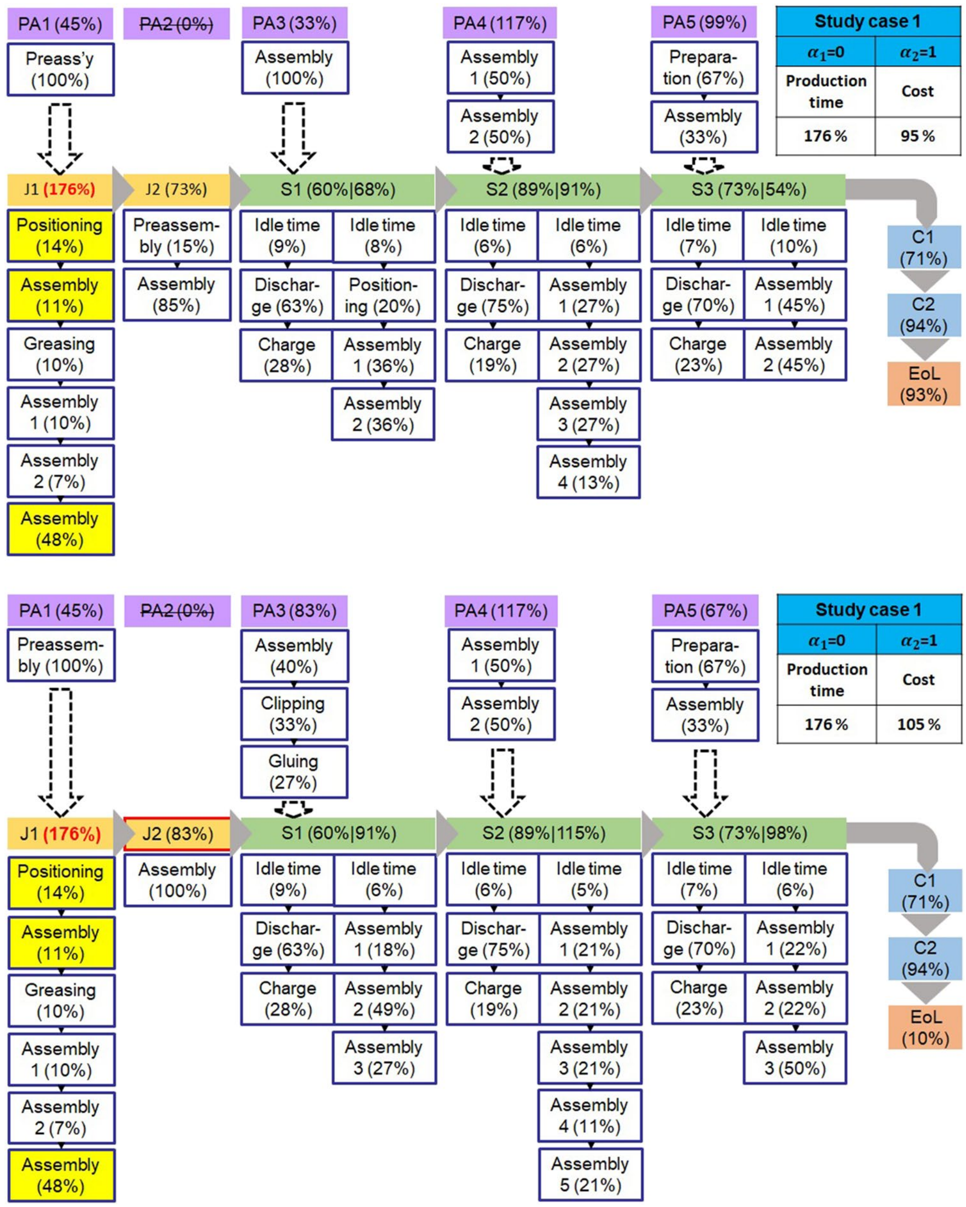


Fig. 11 Detailed result for each of the products and for $\alpha_1 = 1$

three consecutive study cases. The first analyzed the existing system to confirm the correctness of the model and to provide an analysis of bottlenecks. The second conducted a single product analysis with free task-resource allocation and sequencing on different resources to identify possible optimization opportunities. The third one concerned the overall analysis of the system configuration for a product mix of two products. Throughout these applications of the proposed approach, it has been demonstrated that it well-suited for the industrial problem.

For the industrial partner, the application of mathematical modelling for system analysis and optimization has been a new, scientific approach. With its application, the chosen system configuration has been validated in an objective

Fig. 12 Detailed result for each of the products and for $\alpha_2 = 1$



manner. The performance of the global architecture of main line and preparation areas has been highlighted. The main line production time respects the 100% objective for product one. Nevertheless, it became obvious that the completion times of some workstations need to be improved to get an overall production time close to 100%, especially PA5 and S2 for product 2.

Further work will focus on three aspects. The first is the analysis of the optimization potential of structural changes in the screwing section (S1 to S3). The three workstations have the same layout but perform different assembly tasks, even if their technical capabilities are the same. The question is whether there is a performance improvement if the linear serial flow with dedicated assembly tasks is changed into a parallel flow with universal assembly tasks or a hybrid flow.

The second perspective concerns the exploitation of the configuration selection abilities of the developed mathematical modelling. The resource types in the presented study cases have been preselected as the existing assembly line has been examined. Another case study, which is already ongoing, will concern the optimization of a new assembly line during its design phase by selecting different resources and therefore a different configuration based on different cycle time demands. It is therefore a scalability analysis of a future reconfigurable system.

And the last applied research perspective is an investigation of the potential of operational reconfiguration (i.e., task related reconfiguration). As operational reconfiguration can be considered by the developed approach through the notion of adjustment times between tasks and resources, the presented mathematical model can also be used to optimize the assembly line in terms of best task-resource allocation and sequencing choices for multi-product assembly with very small batch sizes, such as for spare parts production.

As the efficiency of the approach among existing literature has not been the focus of the investigation, fundamental research can be carried out on a benchmark comparing the efficiency of the developed approach with those provided in the literature, aiming at determining the performance and the limits of the approach beyond the industrial application.

Acknowledgements The authors gratefully acknowledge the funding by the RDI FlexSpeedFactory, the region Grand Est, and the European Regional Development Fund FEDER as well as the thyssenkrupp Presta France SAS for the cooperation.

Data availability As only real production data of the industrial partner company has been used, no data set can be provided due to confidentiality issues.

Declarations

Conflict of interest The authors declare no competing interests.

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