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Design and management of reconfigurable assembly lines in the automotive industry

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Automotive suppliers are facing the challenge of continuously adapting their production targets to variable demand requirements due to the frequent introduction of new model variants, materials and assembly technologies. In this context, the profitable management of the product, process and system co-evolution is of paramount importance for the company competitiveness. In this paper, a methodology for the design and reconfiguration management of modular assembly systems is proposed. It addresses the selection of the technological modules, their integration in the assembly cell, and the reconfiguration policies to handle volume and lot size variability. The results are demonstrated in a real automotive case study.

Assembly System; Reconfiguration; Co-evolution.

1. Introduction, motivation and objectives

In the recent years, the manufacturing industry is facing new challenges like shorter product life-cycles and increasing demand turbulence. In addition, customers often require a high level of product customization entailing the increase of product variety and the volume reduction [1]. In order to cope with these needs and to maintain their competitiveness in the global market, manufacturing companies are required to quickly adapt their manufacturing assets to the fast evolving market dynamics. Flexibility and reconfigurability have been proposed as effective manufacturing system paradigms to support companies in this transition [2]. In particular, modularity, scalability and functional changeability are technological enablers that can make the reconfigurable systems capable of producing a set of different products with high variety. It has been shown that the impact of these solutions is maximized when the product, the processes and the system co-evolve in a coherent way [3].

This situation is particularly relevant in the automotive industry and even more demanding for automotive car body part (tier-1) suppliers. They are usually demanded to cover automotive part delivery to car-makers in three situations: (i) ramp-up of new models and ramp-down of old models, (ii) part production during the product maturity phase to cover complement Original Equipment Manufacturer's (OEM) production, (iii) supply of spare parts for the aftermarket. As car makers are delivering a growing variety of vehicle models with shorter life-cycles [4], body part suppliers are facing high variability in the volumes, with demand even for very small lots. Moreover, due to the increasing product complexity, increasing number of joining technologies is required in the assembly process. Since the product and the assembly operations are selected by the car-maker, the supplier cannot exploit product or process modifications to meet the co-evolution targets. The only change enabler is the capability of the assembly system to evolve and quickly adapt to changing requirements. In this context, the availability of methods and tools to efficiently design and manage assembly lines that can evolve along the system life-cycle is of paramount importance for the companies' competiveness.

In the literature as well as in the industrial practice, traditional assembly line design approaches usually consider multiple product types but precisely known production targets and neglect uncertainties in the demand volumes and product types [5]. For example, a methodology is developed to support the design of automotive assembly lines with multiple product types to achieve a desired production rate at minimum cost [6]. In [7], a methodology and a software platform to design hybrid automotive door assembly lines, including remote laser welding and resistance spot welding technologies is proposed. In these works, the reconfigurability of the designed assembly system is neglected. Assembly lines with volume flexibility have been analysed in [8], where the possibility to adapt the configuration to different demand scenarios is considered. More recently, methods to deal with capacity planning with consideration of resource reconfigurability was proposed [9] not considering the system configuration problem. Although these approaches provide a scientific foundation to the problem, at the state-of-the-art, formalized methods and tools to support the design and reconfiguration management of modular automotive assembly systems in multi-product and highly uncertain production scenarios are not available.

This paper proposes a multi-disciplinary approach for selecting the assembly technological modules, integrating these resources in an assembly system layout and validating the feasible configurations towards evolving production targets by minimizing a cost function throughout a set of multi-period product demand scenarios. The main industrial objective is to significantly reduce the design time of this complex class of assembly systems and to provide the system the capability to properly adapt its configuration and assembly modules to cope with changing demand along its life-cycle, at minimum cost.

2. Reconfigurable assembly line design problem formulation

Due to the evolution of the market requirements, in terms of part types to produce and their volumes, and the upgrading of the available assembly technologies in time, an assembly line design can easily become inappropriate and can require reconfiguration over time. Therefore, the assembly line design and management method must be able to cope with the evolution of requirements, also addressing how and when the assembly line configuration must change to match the new production needs. To model the uncertain evolution of requirements, a probabilistic scenario model is proposed. A set of nodes Ω is defined, over a set T of periods. For each node, a probability of realization $\pi(\omega)$ is assigned at the beginning of the considered period (t_0). Each scenario node is characterized by a set of production requirements to be guaranteed if the realization of that specific scenario occurs, leading to a tree structure modelling the evolution of the requirements over the time horizon (t_0, t_1, t_2, ...T). The root node represents the current production problem to be addressed and is assumed to be perfectly known.

In detail, the set of products P_ω to be produced is associated to a scenario ω. A volume $d_p(\omega)$ of products in P_ω must be delivered to the customers, under the hypothesis of an average lot size $l_p(\omega)$. For each product p in P, the assembly process requirements are expressed in terms of Functional Assembly Groups (FAGs). FAGs include modular hardware components required for a class of assembly operations, e.g., resistance spot welding, gluing, hemming, self-pierce riveting, laser brazing, remote laser welding, etc. A FAG consists of one or more pieces of equipment, together with the needed tools and fixtures, to carry out the operation. However, resources, such as handling and transportation devices (e.g., robots), can be shared between different FAGs. The FAGs required to assemble a part type P are contained in the set $J_p(\omega)$ and the associated technological requirements, e.g., the number of joints, the hemming length, etc., are contained in the set $\Delta_{j,p}(\omega)$. Unitary processing times required for each FAG (the time per spot or the time per mechanical joint) are provided in the set $M_{j,p}(\omega)$. Furthermore, $S_p(\omega)$ provides the assembly sequence for each part type, typically requiring multiple FAGs. Additional non-operational data regarding each FAG, dealing with the floor space requirements, investment costs, and depreciation years are also taken into account.

The design problem consists in the selection of the FAGs, the classes of equipment within them, and their organization into different assembly cells. Moreover, for each cell, the specific layout, the parts to be produced and the task sequences to be executed are defined. These decisions must be taken with the objective to minimize the expected configuration-reconfiguration costs, over the whole set of scenario branches. Every time a move to a new node happens, a major reconfiguration step can be implemented, to evolve to a new configuration matching the changed production requirements. The aim of the approach is to drive the co-evolution of the assembly line, the product and the process, based on the requirements over the whole set of scenarios, to provide a robust assembly line design solution. In this design problem, robustness refers to the capability of guaranteeing the requested level of performance irrespective of internal and/or external disturbances. This can be achieved acting proactively, i.e., paying for a suboptimal configuration (paying for redundancy or overcapacity) to be ready to manage future changes without the need of reconfiguring; or reactively, acquiring the capability to rapidly react to the changes in the right way (in the considered problem this is enabled by modularity) [10].

3. Assembly system design and management framework

This section addresses the details of the interactions among the modules composing the developed multi-level platform shown in in Fig. 1. These modules exchange data and results in order to deliver a path of reconfigurations for a specific set of product/process evolution scenarios and to support the short-term management of these reconfigurations. For each scenario, a "*design synthesis module*" analyses the market context and proposes feasible designs of the production system, showing a comparative overview of the static performance of these configuration candidates. In this context, an initial set of FAGs to be integrated in the system configuration is selected, together with the needed equipment and the assignment of parts to single/multiple assembly cells. This output is processed by the "*assembly system configuration module*", which integrates these FAGs into a physical layout in a technically feasible way and analyses the dynamic performance measures to find feasible assembly system configurations, against requirements. Based on this output, a "*production planning and simulation module*" determines and validates, over a short-term planning horizon, the best sequence of orders and their batch sizes to be produced in the system within the period, and simulates the solution by discrete-event simulation (DES) to verify the achievements of the target dynamic performance measures, under the optimal batch sizes. The integrated analysis performed by these modules provides for each branch of the scenario tree a path of reconfiguration options, considering modular FAGs replacement (time-consuming reconfiguration) and tool replacement (fast reconfiguration or set-ups) as change degrees of freedom of the system. This information is processes by the external *reconfiguration planning module* that finds, along each path, the set of optimal reconfiguration paths by estimating the expected configuration cost over the scenario tree.

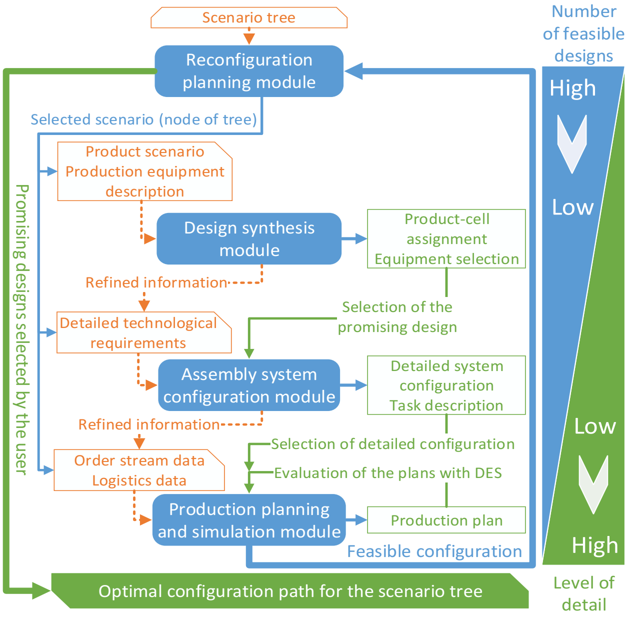


Fig. 1. Workflow for the design and management of modular reconfigurable assembly systems.

All in all, the implementation of this platform makes it possible to configure an automotive assembly line with modularity capabilities and allows the user to properly manage the reconfigurations to handle product and process evolutions profitably. Within the different modules, both internal and external disturbances are considered. This adds stochasticity to the design and reconfiguration problem and provides robustness to the designed solution, with an increasing granularity and level of detail of the processed information.

4. Description of the individual modules

4.1. Design synthesis module

The *design synthesis module* has the main objective to generate multiple feasible designs of the assembly cells composing the system, to analyse their static performance measures and to verify their feasibility against design constraints. Decisions made in this phase, such as (i) the number of assembly cells in the system, (ii) the selection of FAGs and production equipment in each cell and

(iii) the assignment of products to cells, strongly influence the final system design. This module allows decision-makers to assess the impact of these design decisions on the static key performance indicators (KPIs) of the system, including, the total floor space and the cost of each assembly cell, as well as the average lead time of the product in each cell. In order to support these decisions, the knowledge-based tool generates and analyses design candidates in an automated fashion and thereafter visualizes the designs and their static KPIs to enable concurrent system engineering by interactions with the user.

As visualized in Fig. 2, the product data for the scenario under analysis and the descriptions of available equipment components are the main input data for this analysis. The major categories of equipment components to be considered in this design step are distinguished by their function in the assembly cells: part and tool manipulation; part input and output; functional processing in FAGs. For each hardware instance available for system design, the spatial, process-related and economical properties are described in the input database. The synthesis constraints can be formulated by the designer in terms of boundaries for design parameters or KPIs, such as investment costs, space requirements and production lead time and volumes.

To direct the automated synthesis and analysis of system design candidates, an algorithm reads the information from the input database and determines the upper and lower boundaries of each system design parameter. Two heuristics direct the design synthesis process: one heuristic yields production systems where each cell is based on the technological requirement of a specific product family; the second heuristic allows more randomness, resulting in a broader range of values for the design parameters describing the resource-cell allocation. After that, the algorithm gradually instantiates the system design parameters in a random fashion based on their respective range of allowed values. For each system design parameter, it is checked whether the assigned parameter value leads to a design that satisfies the constraints specified by the user. When a design parameter value violates the constraints formulated by the user, a new solution is generated. In this manner, a full specification of the system design is achieved by complementing the description of the assembly system design in regard to quantity and type of the equipment components. Analogous to the two heuristics for parametric system design system, two modes are available for assigning products to cells and to resources. Either one cell is chosen for production of one product family or one route through the production system is assigned for each product individually. Once all products are allocated, the design is completely specified and the static KPIs are determined. As cornerstone of design support, a design knowledge base contains the logic and analytic dependencies of design synthesis and analysis of the distinct application environment, relating the input information to design solutions and their performance.

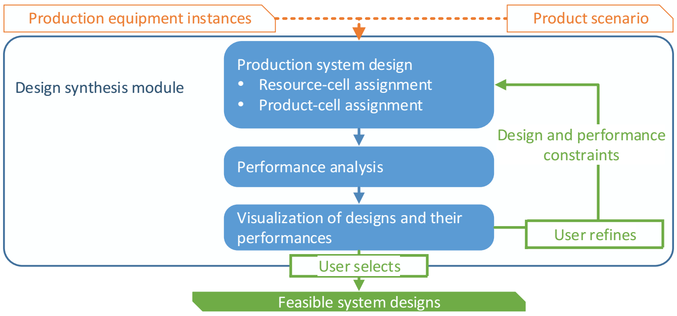


Fig. 2. Workflow of the design synthesis module.

Depending on the degrees of freedom granted by the user, the described procedure can be applied to generate and analyse large numbers of substantially different, feasible design solutions. As output of the tool, the generated designs of the assembly system that meet the requirements of the user are presented and, furthermore, a comparative overview of the relevant static performances of each system design candidate is visualized.

The approach aims at supporting the creativity of designers by enabling them to assess multiple designs of the assembly system that were generated through the computational power immanent to design automation [11]. The module enables the set-based exploration, comparative evaluation and choice of feasible designs of the production system by visualizing solutions and their performance measures. Thereby, it contributes to diminish the time needed for generating and assessing a large number of design candidates and it improves the quality of the provided solution, by supporting the goal of right-fist-time system designs.

4.2. Assembly system configuration module

Once a set of promising designs is identified, each solution must be evaluated with a higher level of detail to assess its dynamic performance measures against the production requirements.

Specifically, the performance of an assembly system is strongly influenced by the detailed layout and the task sequencing chosen to execute the operations in the available FAGs. Thus, the performance of a given hardware configuration strongly depends on the detailed task sequencing implemented. The objective of this module is to compare different design options (layout and task sequence) in terms of dynamic production performance by a fast analytical method, also considering resource dependent stochastic failure and repair parameters, and set-up times.

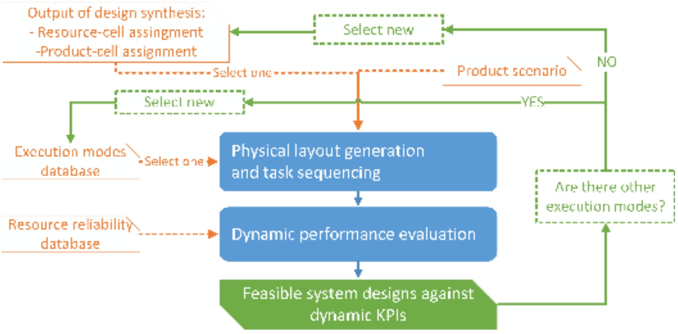


Fig. 3. Workflow of the assembly system configuration module.

The organization of the *assembly system configuration module* workflow is reported in Fig. 3. The module considers as initial input (i) the feasible product-cell and resource-cell assignments, from the design synthesis module, and (ii) the product data, from the scenario analysis. Firstly, the problem of generating a feasible physical layout and task sequencing option for a single design solution provided by the synthesis tool is tackled. This phase considers as additional input a database of feasible task execution modes within a FAG. A task execution mode is defined as a specific technically feasible arrangement of resources and a possible sequence of tasks that the specific resources can perform to execute an operation on the product. An example of task execution modes for a Resistance Spot Welding (RSW) operation are reported in Fig. 4. The physical layout generation phase selects, for each FAG involved, a specific execution mode and composes these execution modes, considering possible sharing of the resources among the FAGs. Then, a compliant task sequence for the assembly cell is generated, using a different approach, inspired by the concurrent theory [12] and process algebra.

In brief, every resource j is associated with a set of states A_j. The whole FAG is then characterized by a state $\Gamma=\{\alpha_1, \alpha_2, ..., \alpha_J\}$. A set of events Θ is defined; an event θ brings the whole FAG from a <pre-condition> state Γ_1 to a <post-condition> state Γ_2. Therefore, an event is described by a logical expression linking a pre-condition to a post-condition. For example, for the first event of the first execution mode of Fig. 4:

$$\theta_i: \Gamma_1=\{U, I, I, (2,I)\} \to \Gamma_2=\{I, I, I, (2,U)\} \tag{1}$$

where U represents an operational state, and I an idle state. For the 7-axes robot, the first state indicator is the position (1: module, 2: mould). By composing these events and linking the states of those resources that are shared among FAGs, the dynamic behaviour of the whole assembly system, including the existing interactions among FAGs, emerges.

In the second phase, a dynamic model of the assembly system, behaving under the specific layout and task sequence defined in the first phase of this module, is derived and dynamic system KPIs are calculated. This activity considers as additional input the database containing the Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) of each resource, as provided by the equipment manufacturer. Moreover, the specific processing times for the tasks carried out in the FAGs, for each part type, the part-type dependent set-up times as well as the average lot sizes are imported by the scenario description. According to these data, the stochastic distribution of the duration of each event reported in the event set is gathered, and the dynamic behaviour of the system is approximated by a continuous time Markov Chain. The evaluation of the main performance measures of the system, such as the average throughput, the average lead time and the distribution of the lot completion time for the given lots are calculated by using the method developed in [13].

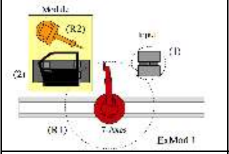
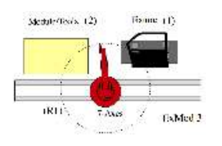
	R1 loads the part from turn table (1) Movement of the robot R1 to the module R1 Releases the part in the fixture (2) R2 Joins the subassemblies Loading the part on the handling robot R1 Movement of the robot R1 to the turn table (1) R1 releases the part in the mould
	R1 loads subassemblies on the fixture (1) Movement of the robot to the module (2) Loading of the welding gun on the robot R1 Movement of the robot R1 to the fixture (1) R1 joins the parts Movement of the robot R1 to the module (2) R1 releases the tool and loads the clamp

Fig. 4. Example of combination of resources and operations into technically feasible execution modes within a FAG.

The main innovation proposed by this module is the automatic generation of feasible material flow dynamics in the assembly system, starting from a static selection of resources in FAGs. After the main KPIs have been assessed, the performance of the system under a new operational mode of the FAG(s) can be explored. If no more operational modes to investigate are left, a new feasible selection of equipment and assignment of parts to cells can be imported and the analysis is restarted. The output of this module is a set of detailed layouts, the related operational modes of the FAGs, the task sequencing and the estimated dynamic KPIs.

4.3. Production planning and simulation module

Based on the detailed cell designs and the production parameters provided by the layout configuration module, the *production planning and simulation module* is responsible for testing the robustness of the designed system under specific due-dates imposed by the customers. The first production planning activity optimizes the production schedule and the lot sizes for user-defined due-time performance. Besides, a simulation tool evaluates the defined system configuration under the specific schedule, considering the effects of stochastic parameters and random events on logistics-related performance indicators. The input of the production planning activity are the set of products that are assembled in the system, the number of available resources, the detailed layout of the system as well as the due-dates coming from the customers. Due dates can be predicted in the early system configuration stage by knowing contractual delivery frequency requested by the customer, and they have significant impact on the applied production lot-sizes and, therefore, the operational costs.

The simulation tool is directly linked with the production planning activity, as the main inputs of the analysis are the calculated production plan, the system configuration with detailed data of the processes, as well as logistics related data, e.g. actual inventory and backlog levels. Production planning is done on a discrete time horizon W, the resolution of the plan is a working shift *(w)*. The objective is to calculate the production lots $x_{p,w,c}$ respecting the available capacities, cycle (t_p^m) and setup (t^s) time constraints. In the model, setups are expressed with the binary variables $z_{p,w,c}$ and $y_{p,w,c}$. When assembling a certain product type, a definite amount of FAGs $r_{j,p}$ is required, and a given amount n_j of FAGs from each type j is available for use at the beginning of the period. The order demands d_p need to be satisfied by delivering certain amount $s_{p,w}$ of products to customers. In the production planning, holding inventory of products $(i_{p,w})$ is allowed, however, it has certain costs c^i. Similarly, planned backlogs $(b_{p,w})$ might occur, but they are also penalized with cost c^b per product and shift. The objective (2) of the problem is to minimize the total backlog and inventory costs that incur in the period. Production planning is formulated as an integer programing problem:

$$\min \sum_{p\in P}\sum_{w\in W}\left(c^b b_{p,w} + c^i i_{p,w}\right) \tag{2}$$

$$\sum_{c\in C}\sum_{p\in P} r_{j,p}\, y_{p,w,c} \le n_j \qquad \forall w, j \tag{3}$$

$$\sum_{p\in P}\left(t_p^m x_{p,w,c} + t^s z_{p,w,c}\right) \le t^p \qquad \forall c, w$$

(4)

$$d_p \le s_{p,w} \quad \forall p, w \tag{5}$$

$$i_{p,w} - b_{p,w} = i_{p,w-1,c} - b_{p,w-1,c} - s_{p,w} + \sum_{c\in C} x_{p,w,c} \quad \forall w, p \tag{6}$$

The first constraints include the limited amount of FAGs (3) and human capacities (4). Inequality (5) states that demands must be fulfilled, and the balance equation (6) links the subsequent production shifts. For the calculation of the setups ($z_{p,w,c}$ and $y_{p,w,c}$), the multi-item single-level lot sizing model was applied *(LS-C-B/M1)*, as presented by Pochet and Wolsey in [14]. The cell-product assignments *(*$a_{p,c}$, equals 1 if product p is assigned to cell c, 0 otherwise) are determined by the previous modules, however, the assignment of resources to cells need to be optimized by the production planning module, in order to avoid conflicts.

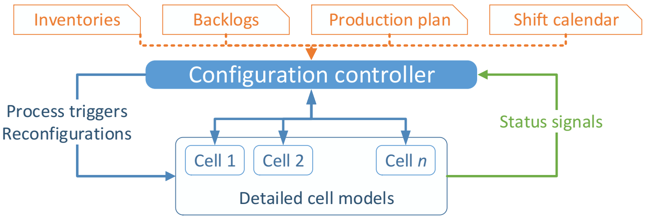


Fig. 5 Architecture of the simulation model with the static configuration controller and the dynamically changing detailed cell models.

The plan resulting from the above model can be executed in a discrete-event simulation (DES) environment, which represents the real production environment with stochastic parameters and random events. In this way, the deviation of the manual processing times, improper material supply processes and random machine breakdowns can be introduced in the analysis. As reconfigurable assembly systems require special simulation approaches due to the dynamic changes of the configurations, a novel simulation modelling technique was applied [15]. The model has both static (configuration controller) and dynamic parts (detailed cell model), which ensure the consideration of architectural changes of the analysed system. The configuration controller is responsible for linking the cell models with the logistics processes (in-/outbound logistics, inventory etc.), as well as to trigger the reconfigurations. The output of this module is a simulated and validated reconfigurable assembly system design which produces the required product volumes with optimized lot sizes to respect the customer due dates.

4.4. Reconfiguration planning module

A different perspective must be adopted when addressing a longer time horizon, as described in Section 2. The set of products P to be produced can vary over time and also the assembly cells in the system could need to be suitably reconfigured. It could be necessary to dismiss pieces of equipment or insert new ones or move them among assembly cells. These decisions must ground on the evolution of the production requirements modelled through the scenario tree in Section 2. As these requirements change, moving along nodes in the tree, the design of the cells can change as well, thus undergoing reconfiguration.

In the *reconfiguration planning module*, all the possible evolutions of an assembly line's configuration are considered. Each of them refers to a specific path from the root of the scenario tree to a leaf and is associated to an occurrence probability. Nevertheless, different paths in the tree share a subset of nodes and, in this subset, they must also share the same configuration. Given this set of constraints, it is possible to formulate an optimization problem, looking for the best reconfiguration steps for the different scenarios, with the aim at achieving robustness over the whole scenario tree. In some cases, it will be advisable to acquire resources in advance or, if the occurrence probability is low, to wait until a specific scenario occurs and, hence, acquire the needed pieces of equipment.

The reconfiguration strategy aims at minimizing an objective function (7) considering the expected value of the incurred cost over all the scenarios [16]:

$$min\left(IC_0(e) + OC_0(e) + \sum_{\omega\in\Omega_s}\pi_\omega \frac{IC_\omega(f|e)+OC_\omega(f|e)}{(1+q)^{stage\ \omega}}\right) \tag{7}$$

where IC_ω and OC_ω are the investment and operation cost in scenario node ω (Ω_s is the set of scenario nodes) and depend on the initial configuration decisions (e) and the reconfiguration actions (*f*); for the root node (node *0*) they only depends on *e.* The discount rate is q and $stage_\omega$ is the time stage of the considered scenario node. Only the configurations respecting the production requirements and generated at different levels of detail by the modules described in Sections 4.1, 4.2 and 4.3 are considered for the optimization. The output of the proposed approach is an initial configuration for the assembly lines, together with appropriate reconfiguration steps associated to the different nodes in the scenario tree.

4.5. Interoperability and integration of the platform

The developed modules have been integrated into a common software platform. Each of the functional modules can be triggered in independent mode directly from this platform, which employs the modules as black-boxes and offers an intuitive web-based GUI on role-basis. Additionally, the integrated platform also offers a workflow mechanism where the modules are chained sequentially, operating on the same database. This central database ensures the interoperability of the modules by the Core Manufacturing Simulation Data (CMSD) standard model [17].

Following the organizational structure of a production company, within the integrated platform different roles can be granted with different data access levels. As such, this guarantees that different users will be able to access only data they have permission to access. Although, as presented, the workflows follow strictly sequential logics, backward feedback is allowed in the platform, making it possible to use the different modules in loops. A loop is called 'an experiment', i.e. a singular user-driven analysis characterized by a set of input parameter values and the results. Within a scenario the integrated platform allows the users to generate, run, save and compare a set of experiments that were set-up, thus enabling high level of interaction with the user.

5. Application to a real case study in the automotive industry

The practical relevance of the framework was proven in an industrial case study provided by an automotive company, first tier supplier of vehicle body parts managed in built to order mode. Due to the increasing number of car body variants offered by original equipment manufacturers (OEMs), a fragmentation of the absolute demand volume makes necessary a change in production particularly for spare parts, whose declining volumes make economic production an increasingly challenging endeavour. Consequently, the frequent design, implementation and reconfiguration of the assembly line is a suitable concept to proactively manage the variable product volumes. To support these tasks, a scenario tree is considered, describing multiple, anticipated developments of production requirements (Table 1). The scenario nodes are named according to the time period they refer to, hence $\boldsymbol{\omega_0}$ is the root node while $\boldsymbol{\omega_{1A}(\omega_0)}$ is a node related to time period 1 whose ancestor node is $\boldsymbol{\omega_0}$. For each node, the production volumes for the different products are considered (products are not explicitly reported for confidentiality reasons). Also the FAGs requirements for each product are reported. For each class of operations, we refer to needed tools and process times. E.g., product *1* requires the Mechanical Join FAG using tool *T1* for 10 seconds; product *3* also requires that FAG using tool *T1* for 25 seconds and *T2* for 8 seconds (Table 1, last three rows).

Table 1. Product demand scenarios and process information for input

	Products			
Scenario Nodes	**Prod. 1**	**Prod. 2**	**Prod. 3**	**Prod. 4**
$\boldsymbol{\omega_0}$	7 500	0	9 000	0
$\boldsymbol{\omega_{1A}(\omega_0)}$	0	0	8 500	7 500
$\boldsymbol{\omega_{1B}(\omega_0)}$	0	0	7 500	5 000
$\boldsymbol{\omega_{2A}(\omega_{1A})}$	5 200	8 300	4 800	2 300
$\boldsymbol{\omega_{2B}(\omega_{1A})}$	5 000	8 000	4 500	2 000
$\boldsymbol{\omega_{2C}(\omega_{1B})}$	4 500	700	4 500	2 000
$\boldsymbol{\omega_{2D}(\omega_{1B})}$	4 000	6 500	4 000	2 000
$\boldsymbol{\omega_{2E}(\omega_{1B})}$	3 500	600	4 000	2 000
FAGs				
OP1: Mechanical Join (Tool-ID, Duration)	T1, 10s	-	T1, 25s T2, 8s	T1, 18s
OP2: Resistance Join (Tool-ID, Duration)	T1, 192s	T1, 102s	T2, 177s	T2, 198s
OP3: Adhesive Join (Tool-ID, Duration)	T2, 25s	T1, 27s T2, 13s	-	-

Based on this input information, the proposed approach has been applied for each of the considered scenario nodes. First the design synthesis module generates design candidates according to different production strategies and analyses their performances. To cope with the large solution state space, design and performance constraints can be imposed: performance, investment cost and maximum number of FAGs implemented in a cell have been used for this application case.

A more detailed evaluation of the initial set of designs is achieved refining the solutions through the assembly system configuration module, to define the detailed layout and task assignment. For each candidate layout configuration and execution mode, the performance evaluation tool is used to assess the dynamic KPIs of the solution and to identify the unfeasible alternatives. Finally, the production planning and simulation module provides decision-support for operative management of the production system. The importance of analysing alternative tactical operations is justified by the significant operational costs that incur during a reconfiguration period. According to the test results, these costs are in the same order of magnitude with the investments. This sequence of analyses is performed to identify a final set of feasible solutions for all the different nodes in the scenario tree. Hence, the reconfiguration planning module is used to identify the optimal sequence of configurations and reconfigurations, to cope with the different scenario paths.

Table 2. Numerical results for the industrial real case.

	Cost Type	t1	t2	t3	Total
robust approach (overall approach)	FAG purch.	358 883	0	0	358 883
	module purch.	50 000	0	0	50 000
	reconfiguration	0	0	0	-
	storage	0	12000	0	12.000
	operative	92 010	106 002	78 894	276 906
	tool purch.	45 000	20 000	20 000	85 000
	total (discount)	545 893	133 412	92 425	771 730
single path optimum (best configuration is chosen for each scenario)	FAG purch.	358 883	0	0	358 883
	module purch.	40 000	0	10 000	50 000
	reconfiguration	0	10 000	10 000	20 000
	storage	0	18 000	0	18 000
	operative	100 776	103 542	83 850	288 168
	tool purch.	45 000	20 000	20 000	85 000
	total (discount)	544 659	146 502	115 748	806 909
single node optimum (best ω_0 configuration is used in every scenario)	FAG purch.	358 883	0	infeasible solution	358 883
	module purch.	40 000	0		40 000
	reconfiguration	0	10 000		10 000
	storage	0	18 000		18 000
	operative	100 776	103 542		204 318
	tool purch.	45 000	20 000		65 000
	total (discount)	544 659	146 502	-	691 161

The results of the whole approach applied on scenario path $\boldsymbol{\omega_0} \rightarrow \boldsymbol{\omega_{1A}} \rightarrow \boldsymbol{\omega_{2B}}$ are reported in Table 2. First row refers to the robust solution, obtained by applying equation (7). Second row refers to the optimal solution for the considered scenario path only, obtained by choosing the best configuration solution at each step (reconfiguration costs foreseen). Last row reports the solution in which optimal solution for $\boldsymbol{\omega_0}$ is used in every time bucket. The solutions are compared in terms of purchasing, reconfiguration, storage and operational costs. Results demonstrate that the robust solution ensures a lower total discounted cost compared to the optimal solution for the single scenario path (771 730 € against 806 909 €), the difference is mainly due to the fact that the robust solution behave proactively, purchasing additional pieces of equipment in advance, while the other solution has to react to the changes through a reconfiguration step, whose impact on the cost is relevant (10 000 €).

Finally, the comparison with the optimal single node solution shows that, although it has a lower total cost, without a reconfiguration, the layout results to be infeasible in scenario $\boldsymbol{\omega_{2B}}$, being unable to match the production requirements. The layout of the assembly cell in the robust solution identified by the proposed approach is represented in Fig. 6, showing the modules, the tools and the robots installed.

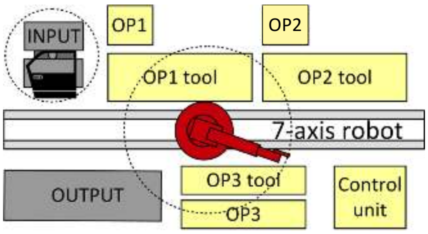


Fig. 6 Detailed output layout of the assembly cell.

6. Conclusions and discussions

In this paper, a comprehensive methodology was introduced for efficient design and management of modular reconfigurable assembly systems. The workflow is aimed at reducing the overall design time and efforts through modules, incrementally adding details to the solution of the previous step to support design and planning decisions. The applicability of the proposed method is justified by an industrial case study of an automotive supplier of body parts. Future research will be devoted to the extension of the approach to include manual assembly stages, thus enabling the extension to a broader set of industrial assembly systems.

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