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An Approximate Analytical Method to Evaluate the Performance of Multi-Product Assembly Manufacturing Systems

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Abstract

The automotive industry is characterized by the continuous and frequent adoption of cutting edge technologies in manufacturing. The introduction of new technology often entails a system level investigation to determine whether it meets expected production requirements. Many system design alternatives are usually considered at this stage, and a fast performance evaluation tool is desired to quickly obtain the optimum system configuration. In this paper, we introduce an analytical tool that was developed for this specific purpose.

The investigated manufacturing system is a multi-product, automated, assembly production line composed of unreliable machines decoupled by finite buffers. Each product is an assembly of two components that are produced in sub-assembly lines before being assembled at an assembly machine. The performance of this system needs to be evaluated for different configurations that arise mainly due to the integration of a remote laser welding technology. This new technology promises, among other advantages, a much faster assembly than existing technologies. This makes it feasible to share assembly among many products with different possible production policies. The processing machines including the assembly machine are liable to fail randomly in operation thereby necessitating an evaluation method capable of accounting for stochastic behavior.

To solve this problem, we develop a decomposition-based approximate analytical method. We use the continuous material flow approximation, which allows to model machines having deterministic but inhomogeneous processing times as in the investigated real system. We also account for multiple machine failure modes and introduce new techniques to incorporate the assembly of multiple products with different policies of switching between products. Comparison with simulation results shows the good accuracy of the model in estimating system throughput and work-in-progress. The model has been successfully utilized to evaluate the performance of an automotive door assembly manufacturing system and the main results of this case study are reported.

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1. Introduction

Due to the increasing complexity in the material flow found in modern manufacturing systems, knowledge-based tools and methods are seen as fundamental enablers for supporting decision making during the system design, reconfiguration and operation phases ([1]). Approximate analytical methods are being increasingly promoted as faster and more intuitive alternatives to simulation in the

performance evaluation of industrial production systems ([2]). An excellent review of these methods can be found in [3]. Several researchers have developed approximate analytical models for manufacturing systems with assembly operations, including [4], [5], [6] and [7]. Among these papers, [4] analyzed assembly production systems for the cases where machines had multiple failure modes. However, this model assumed homogeneous production lines. Furthermore, in all of these papers, only single product assembly was considered.

Due to the shorter product life-cycles and the increasing set of product variants to be assembled in the same automated system ([8]), more and more assembly systems are endowed with technologies which are designed to be flexible and able to operate on more than one product. For example, remote laser welding is an emerging technology in automotive body welding that presents several benefits with respect to the traditional resistance spot welding process, being able to operate welding on a wide variety of products, including doors, bonnets, and tailgates. However, in order to exploit these technological features, an optimized system design needs to be generated.

Multi-product manufacturing systems have been analyzed by [9-15] among others. In [10] and [11] in particular, the authors analyzed systems having automated machines with multiple failure modes. However, these models did not incorporate assembly operations. Currently, the case of multiple products can only be treated by approximating the multiple product flows as an aggregated flow of an averaged and fictitious equivalent single product. However, this approach leads to accurate results only if the processing times and the reliability parameters for the two or more products are the same. Otherwise, the accuracy of this approach is very poor if the results are compared to DES. To the best of our knowledge, there are no analytical models for the performance analysis of multi-product assembly manufacturing systems.

The objective of this paper is to develop a new analytical approach to evaluate the performance of multi-product assembly systems with product-dependent processing rates and unreliable machines, subject to multiple failure modes. The application of the developed approach to a real case study in the automotive industry, which is part of the EU funded project RLW Navigator, is also reported.

The paper is structured as follows. In the next section, a description of the system is provided and the main modeling assumptions are reported. In section 3, the behavior of a multi-product assembly machine in isolation is described in details. In section 4 the method used to evaluate the performance of the system is described while in section 5 its application to a real assembly line in Jaguar Land Rover is described.

2. Methodological approach

2.1. Description of the multi-product assembly system

The considered multi-product assembly system is a directed continuous flow network formed by NS stages and BS buffers of finite capacity, configured in a non-linear layout. A schema of such a system is reported in Fig. 1.

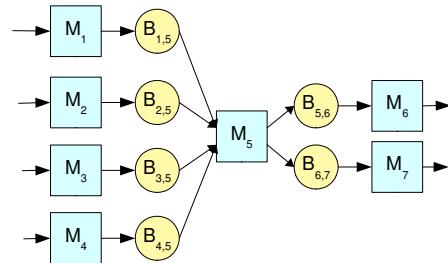


Fig. 1: Representation of a multi-product assembly system.

Stages (squares), interchangeably named workstations or stations, in the set M , are denoted as S_k , $k=1,..,NS$, and buffers are denoted as $B_{i,j}$ where i and j refer to the upstream and downstream stages, respectively. The capacity of each buffer is $N_{i,j}$, that is a real number. The topology of the system is described by the set Γ of its directed connections, or branches, from stage i to stage j .

More formally:

$$\Gamma = \{(i, j) | i \in M, j \in M\}$$

Each workstation is composed of production resources, including robots, turn tables, etc. In general terms, it is possible to have different kinds of workstations according to the following criteria:

- **Operation type.** From this criterion it is possible to characterize a workstation as a *manufacturing* or as an *assembly* stage. An *assembly* stage is a set of resources such that a series of components are joined together to create a single product.
- **Part type number.** From this criterion it is possible to characterize a workstation as *dedicated* or as a *flexible* stage. A *dedicated* stage is a set of resources such that it is possible to process just one part type. On the contrary, a *flexible* stage is endowed with the capacity of processing more than one part type.

In this paper, we are interested in the description of a *flexible assembly machine*, or a *multi-product assembly machine*. In practical terms, such a machine is a set of resources that perform an *assembly* process for more than one finished products.

The system is assumed to process Z assembled products that can be seen as the finished products. A multi-product assembly machine S_k can process different assembled products, according to a part mix vector Z_k . A vector Z_k has size equal to Z and each element z_k of Z_k will be equal to 1 if machine S_k can make product z , otherwise it will be equal to 0.

The system is assumed to have U raw components used in the assembly process. The correspondence between raw components and assembled products is done according to a correspondence matrix U_k whose size is equal to U rows and Z columns. An element of U_k is equal to 1 if component u_k is used for assembling product z_k .

Each workstation S_i processes product z with a deterministic cycle time $CT_{i,z}$ [time/job]. The processing rate $\mu_{i,z}$ is the inverse of the cycle time [jobs/time]. Moreover, each station S_i is subject to F_i different causes for failure, each one related to a specific resource or component in the station and characterized by its specific MTTF (Mean Time To

Failures) and MTTR (Mean Time to Repair). Time To Failures and Time To Repair of components are considered to be exponentially distributed random variables.

2.1.1. Characterization of machine states and behavior

The workstation states are described in the following. Consider a workstation that can process two parts ($Z=2$), each one with its own deterministic processing rate. For example, we can use machine M_5 from Fig. 1. Product 1 is made out of components 1 and 2, contained in Buffers $B_{1,5}$ and $B_{2,5}$ respectively. The assembled product is stored in Buffer $B_{5,6}$. Product 2 is made out of components 3 and 4, contained in Buffers $B_{3,5}$ and $B_{4,5}$ respectively. The assembled product is stored in Buffer $B_{6,7}$.

The operation requires a deterministic cycle time CT_1 for product 1 and a deterministic cycle time CT_2 for product 2. The workstation starts processing product 1 and during this period the station is in a working state, processing product 1. After a time equal to CT_1 , if the station did not fail while processing, the station is ready to unload the worked part and to start a new operational cycle. However, if any of the downstream buffers is full, the workstation enters into a blocking state (i.e. the machine is blocked) and has to wait before the processed part can be unloaded. Conversely, if any of the upstream buffers storing components are empty, the station cannot load a new part and is said to be idle or starved. Moreover, if none of these situations happens, then part 1 is unloaded in the corresponding buffer and a new product 2 is loaded for processing. During this period the station is in a working state, processing product 2. After a time equal to CT_2 , if the station did not fail while processing product 2, the station is ready to unload the worked part and to start a new operational cycle on product 1. Therefore, each workstation can be in one of different mutually exclusive states: working product z , starved for at least one of the components needed by product z , blocked for product z or down.

2.1.2. Machine policies

We assume that if the flexible machine processing multiple parts is starved or blocked for a specific product type, the machine cannot switch to another available product but it has to wait for the starvation or blocking conditions to be restored before finishing the production on the specific product and then switch to another one. The reason for this assumption is to ensure a given part mix. Also, we assume the sequence of products to be processed is fixed (*cyclic policy*) and stored in a proper sequencing vector ZS_k , with $k=1,\dots,NS$. Each vector has size Z and each element is the number of times that a given part is processed before switching to the next one. For example, if station M_1 processes one part of type 1 and then one part of type 2, ZS_2 will be equal to [1 1]. If station M_1 processes two parts of type 1 and then one part of type 2, ZS_2 will be equal to [2 1].

2.1.3. Other assumptions

The discrete flow of parts is approximated by a continuous flow model. Indeed, asynchronous production lines where stages have unequal but deterministic processing times can be suitably modelled through the use of continuous flow models.

These models approximate the behavior of asynchronous discrete material flow lines by considering workstations that act as valves that process the material flow at different speeds. Therefore, the minimal “atom” for our system model is the workstation level. The resource or component level is only considered for generating the reliability data of the workstation.

Further assumptions are required for completely describing a multi-product assembly machine:

- Input machines are never starved and output machines are never blocked.
- Failures are operation dependent, i.e. a station can fail only during an operational cycle.
- Failures do not overlap, i.e. a station cannot be failed in more than one mode at the same time.
- Transportation times are not modelled. They are included in the cycle time of the upstream workstation.
- Setup times for switching between part types are considered as negligible.

3. Flexible assembly machine in isolation

In this section, we provide a Markovian approximation of the behavior of the flexible, multi-product assembly machine in isolation, i.e. if it is not impeded to produce by the other machines in the system. One of the most limiting assumptions of Continuous Time Discrete State Markov chains is to consider exponential time of transitions between states. The exponential distribution has a standard deviation that is equal to its mean. A deterministic event has a standard deviation equal to 0. However, it is possible to approximate deterministic events within Continuous Time Discrete State Markov chains by exploiting the features of the Erlang distribution. The Erlang distribution, also denoted as $E(\lambda,k)$, is an example of Phase Type distributions and is the distribution of the sum of k independent identically distributed random variables each having an exponential distribution. The state transition diagram of an Erlang distribution is represented in Fig. 2.

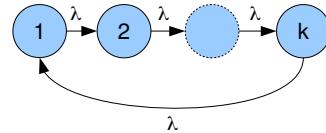


Fig. 2: Erlang distribution to approximate deterministic events

It can be shown that the mean of the Erlang distribution is equal to k/λ where k is the number of states or phases used to describe the process and λ is the transition rate between the phases, and the variance of this distribution is k/λ^2 . In other words, as the number of phases increases, the squared coefficient of variation of the distribution decreases, meaning that the deterministic duration of the event is approximated better and better. The grace of this approximation is that we can control the goodness of fit. In other words, by increasing the number of phases, i.e. the complexity of the model, we can reduce the error in the approximation of the deterministic event.

As a result, we can use Erlang approximation for modelling deterministic cycle times for each product and, according to the specific sequence, we can build an approximate Markov chain of the flexible machine producing multiple parts. Once the number of phases of the Erlang is fixed, the parameter λ for product z can be obtained as a function of the mean of the distribution that needs to be matched as $\lambda = k/CT_z$. For example, consider a machine processing 2 products according to the sequence ZS=[1,1] having a single failure model with failure rate p and repair rate r . The machine takes 10 seconds in processing product 1 ($CT_1=10$) and 30 seconds for product 2, ($CT_2=30$). The Markovian model of this flexible machine can be approximated as in Fig. 3, having selected a number of phases $k=2$ for each product cycle time.

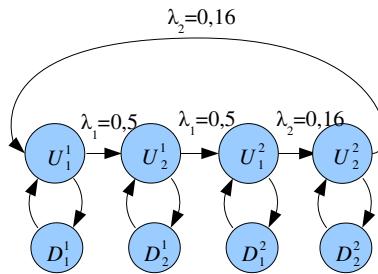


Fig. 3: Example of approximate Markov model for a multi-product machine producing 2 part types.

4. Description of the method

4.1. Main ideas of the developed approach

The approach developed to evaluate the system performance is based on the decomposition idea ([4, 17, 18, 19]). The behavior of a NM stages assembly system is approximated by means of NB two-machine lines. Each two-machine line $l(i,q)$ (Fig. 4) is associated to a specific buffer $B(i,q)$, with (i,q) in Γ , of the original system and can be evaluated by an exact analytical solution [16]. The rationale of the method is that, if it is possible to reproduce in the buffer of each two-machine line the same flow of parts observed in the corresponding buffer of the original system, then the performance measures of the various two-machine lines closely match those of the original system. Decomposition equations are derived in order to find the appropriate values for the unknown parameters, namely failure, repair and processing rates, of the pseudo-machines in the various two-machine lines such that the flow of parts in the two-machine line resemble the flow observed in the original system.

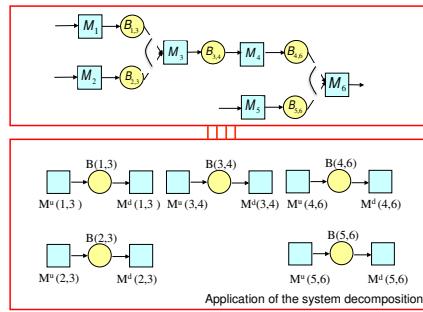


Fig. 4: Application of the decomposition technique for an assembly system.

The flow of parts into a buffer of the original system can be interrupted because the upstream machine fails in a certain mode or because it gets starved (due to the emptying of one of its upstream buffers) or because it gets blocked (due to the filling of one of its downstream buffers, except the buffer under examination). Conversely, in the two-machine line the starvation of the upstream machine cannot occur (being this the first machine of the line). Therefore, to reproduce in the two-machine line the interruptions of flow observed in the original system, remote failure modes for the upstream pseudo machine are introduced. Similarly, the need to take into account all the different reasons that can lead to an interruption of the output flow from a buffer of the original system requires the addition of remote failure modes to the downstream pseudo machine of the two-machine line. This is better described in [4].

4.2. Pseudo-machines' behavior

From theory we know that if multiple products are considered within the Markov chain, a proper set of decomposition equations need to be provided. For this reason, a proper configuration of pseudo-machines is proposed, in order to use the structure of the Markov chain described before in the context of existing decomposition methods for single product assembly. To do this, we use an idea presented in [6], already common in queuing theory, that is the concept of *vacation time*, usually used to mimic a portion of time in which a resource is not working because of some specific reason, i.e. maintenance, setup, etc.

We can consider the example reported in Fig. 1 as reference. Using the decomposition principle, the system can be divided into the sub-system represented in Fig. 5.

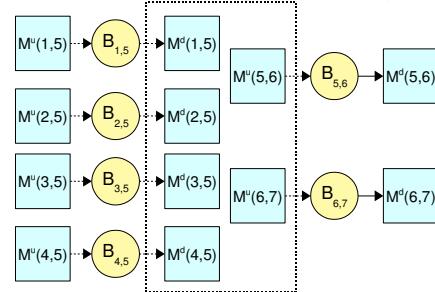


Fig. 5: Building block decomposition of the example presented in Fig. 1.

The challenging part is defining a proper pseudo-machine structure to machine M_5 , that are $M^d(1,5)$, $M^d(2,5)$, and $M^d(5,6)$ for product 1, and $M^d(3,5)$, $M^d(4,5)$, $M^d(5,6)$ and $M^d(6,7)$ for product 2.

In this case, the concept of *vacation time* is used to mimic the fact that a flexible machine is processing another product. For example, let's look at machine M_5 from the perspective of product 1; we can say that when machine M_5 is assembling product 1, it cannot process product 2 at the same time or, machine M_5 is busy with product 1. From this reasoning, all the states of the Markov chain of the multi-product machine related to product 2 can be considered as *vacation states*, when looking at product 1. These states are considered as non-productive states. In following figure, such adaptation is reported.

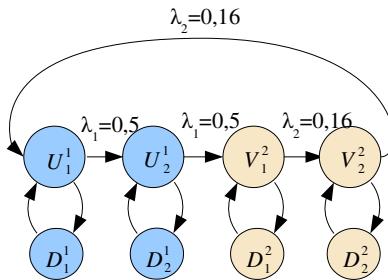


Fig. 6: Example of approximate Markov model for a multi-product machine producing 2 part types, looking at product 1.

Similar considerations can be done while looking at machine M_5 from the perspective of product 2. This structure of the Markov chain can be used to construct pseudo-machines $M^d(1,5)$, $M^d(2,5)$, and $M^d(5,6)$ for product 1, and $M^d(3,5)$, $M^d(4,5)$, $M^d(5,6)$ and $M^d(6,7)$ for product 2, in addition to all states needed for mimicking of flow interruption and resumption (see [19]) for assembly systems. All transition rates between these states (*vacation parameters*) can be chosen according to the corresponding cycle time to process product 2, if the flexible machine is in isolation. However, when a machine is not in isolation, these rates should be adjusted properly in order to consider blocking and starving phenomena when the machine is producing other products. A rule for tuning these parameters is provided.

Now, in order to apply the standard single product assembly decomposition, a proper iterative algorithm is needed. In fact, the whole line is divided into Z sub lines, each one composed by all machines involved in the manufacturing of product z . The flexible machine is modelled using the *vacation time* principle. Vacation parameters V_z for product z are calculated according to the following equation:

$$V_z = \frac{1}{\sum_{i \neq z} T_i} \quad (1)$$

The value of T_i corresponds to the effective time spent by the machine while producing product i . From this equation it is possible to evaluate the performance of different sub lines. Results can be used to adjust all *vacation parameters* of pseudo-machines, considering all steady state probabilities to have machine M_5 according to the following equation:

$$T_z = \frac{CT_z}{p(W)} (1 - p(V_z)) \quad (2)$$

The value of CT_z corresponds to the cycle time associated to product 1, $p(W)$ is the probability of machine M being up and producing product z at maximum speed, while $1-p(V_z)$ includes all probabilities of machine M begin up but starved or blocked while producing product z . This update procedure is repeated until convergence over throughput is met.

In the following, a list of all required steps is reported:

1. Use original system to create Z sub lines, each one dedicated to the assembly of product z .
2. Apply single product assembly decomposition technique to each one of these sub lines, where the flexible machine has *vacation states*.
3. Initialize all *vacation parameters* according to products cycle times, using Equation (1).
4. Execute performance evaluation.
5. Check if the difference between throughput values of all sub lines is small, i.e. $1.0e-4$. If yes, evaluation is concluded.
6. Compute *state sojourn times* from steady state probabilities.
7. Use *state sojourn times* to update *vacation parameters*, using Equation (2).
8. Continue to 4.

5. Industrial case study

The proposed approach has been applied in the reconfiguration of the Z18 and Z19 production systems for car door welding and assembly in Jaguar Land Rover production plant [20]. This reconfiguration involves the application of Remote Laser Welding (RLW) technology in combination with Resistance Spot Welding (RSW). The leading idea is to (1) ensure the respect of all technological constraints derived from product assembly tree specifications and process requirements, and (2) guarantee that the flexibility and performance potentials of RLW technology are optimally exploited, at system level.

The cell Z18 currently includes two identical systems, one dedicated to the production of front left (FL) doors and one to front right (FR) doors, for both 3 door and 5 door models. Rear doors, used only for the 5 door models, are produced in cell Z19 that processes both left (RL) and right (RR) doors, following a fixed 1 to 1 sequence (1 left door and 1 right door in sequence).

Each Z18 cell is composed of 14 robots. The door assembly process involves loading process, welding (RSW), hemming and curing, before it is assembled onto the body in white (BIW). A schema of the assembly process is reported in [20]. These cells are operated by a total of 2 operators, each performing load and unload operations. The most time consuming process is the hemming station. The Z19 cell is composed by 16 robots, following a similar layout as Z18. In this configuration, all cells are independent, with each one having its own dedicated robots.

In [20] several configurations with shared resources have been analysed. For example, one of the most promising

solutions involves a single cell producing both FL – FR and a single cell producing both RL – RR, reducing the number of robots from a total of 44 to 30.

In the reconfigured solution presented, the main idea is to use a single multi-product RLW robot to perform all welding operations, for both front and rear doors. The request that needs to be satisfied by this new configuration is to achieve a desired production level for both front doors and rear doors. The decision variable in this case is the cycle time of the RLW station. Since it is faster than traditional welding technologies, it is possible to set a proper cycle time such that the desired production level is satisfied. All issues concerning technical process feasibility (i.e. robot motion planning, flexible fixture design, etc.) are extensively studied and analyzed in [20].

Now, it is possible to apply the proposed methodology on the real case. This configuration will be producing 4 different products: front and rear left doors, and front and rear right doors. All robots and components are aggregated into production stations, according to the kind of operations that is performed. For each product, 7 stations are considered, for a total of 28. In addition to these 28 stations, one RLW robot should be considered as well. For each part-type, 5 intermediate buffers are added, taking into account the floor space available. The corresponding buffer capacities are equal to 1. A schema of this analysis is reported in the Fig. 7. All failure and repair parameters are taken directly from the producers' database ([20]).

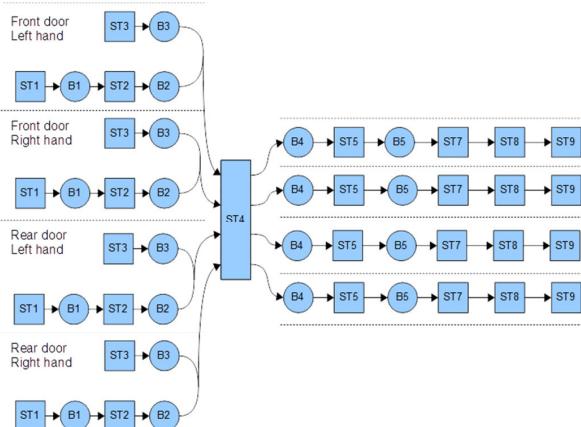


Fig. 7: Schema of four part-type system.

Since the number of front and rear doors is not the same (demand for 3 door models is higher), a proper policy is proposed, namely *9-7 policy*. According to this policy, RLW station will produce a fixed sequence of FL – FR – RL – RR for 7 times and then a fixed sequence of FL – FR – FL – FR for 2 times. This policy guarantees the requested production ratio. From the subsequent analysis, it is possible to show that the requested production level for all four part-types is achievable when RLW cycle time is equal to 55% of the actual value, omitted for confidentiality reasons. In the following Figure, the throughput curves are reported.

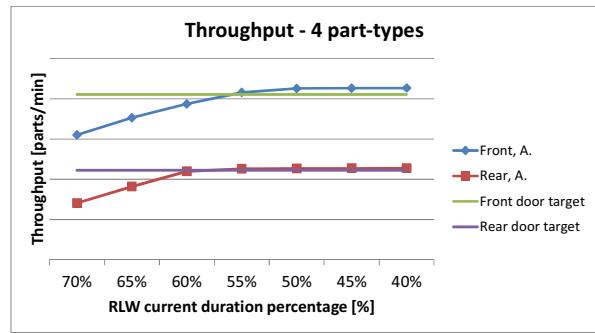


Fig. 8: Throughput curves for proposed configuration. The corresponding absolute values are removed due to confidentiality reasons.

All results obtained with the proposed method have been tested against a proper DES simulation model, in order to provide a preliminary validation tool. In the following Table, the percentage difference between the proposed method and the corresponding DES simulation is reported.

Table 1. Percentage difference between approximate analytical method and DES simulation.

%	Front left	Front right	Rear left	Rear right
70%	-5,72%	-5,72%	-7,55%	-7,55%
65%	-0,10%	-0,10%	-2,91%	-2,91%
60%	0,25%	0,25%	-4,06%	-4,06%
55%	-0,24%	-0,24%	-3,33%	-3,33%
50%	-0,28%	-0,28%	-1,25%	-1,25%
45%	-0,22%	-0,22%	-1,14%	-1,14%
40%	-0,37%	-0,37%	-1,28%	-1,28%

Overall, it has been possible to show that the required target performance is achieved by the currently proposed configuration. In addition, the introduction of such technology can help in reducing overall costs, in terms of energy and occupied floor space. Moreover, the adopted solution can provide the same throughput with fewer robots than the current configuration.

6. Conclusion and further research

This paper proposed an approximate analytical model for the performance evaluation of multi-product assembly manufacturing systems. The model has been used to support the reconfiguration of an existing system for the assembly of car doors, which involved the substitution of all dedicated traditional welding robots with one Remote Laser Welding robot. Results prove that, if properly designed, a flexible resource (RLW) can help the designers by reducing overall system costs, without compromising on performance.

Future research will be focused in a further reduction of equipment costs, i.e. sharing more resources between part-types following the results from [19] and in testing different production policies.

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