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Resource efficient configuration of an aircraft assembly line

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Abstract

The design of efficient assembly systems can significantly contribute to the profitability of products and the competitiveness of manufacturing industries. The configuration of an efficient assembly line can be supported by suitable methodologies and techniques, such as design for manufacture and assembly, assembly sequence planning, assembly line balancing, lean manufacturing and optimization techniques. In this paper, these methods are applied with reference to the industrial case study of the assembly line of a Skycar light aircraft. The assembly process sequence is identified taking into account the analysis of the assembly structure and the required precedence constraints, and diverse techniques are applied to optimize the assembly line performance. Different line configurations are verified through discrete event simulation to assess the potential increase of efficiency and throughput in a digital environment and propose the most suitable configuration of the assembly line.

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1. Introduction

The design of efficient assembly systems is a critical issue that can significantly contribute to the profitability of products and the competitiveness of manufacturing industries [1-3]. As a matter of fact, assembly processes may reach up to 50% of the total production time and account for more than 20% of the total manufacturing cost [1]. A number of methodologies and techniques have been developed to support the design and optimization of assembly systems, with the aim to reduce the associated time and costs at different stages [4-7]. The design for manufacture and assembly (DFMA) approach is aimed at reducing assembly time and costs in the product conception and design stage by offering solutions such as combining a number of workstations that share similar size and assemble similar products [5]. Assembly sequence planning techniques are aimed at identifying the optimal assembly sequence of components at the assembly stage, to improve speed and cost-effectiveness [6]. Assembly line balancing methodologies can contribute to distribute the workloads in the different workstations in the production planning stage.

These methodologies can be valuably supported by the implementation of a digital manufacturing approach, based on the simulation of the assembly processes in a virtual environment [8-12]. Simulation models allow to simulate the processes before carrying out any capital investments, and process lines can be optimized exactly to their specification and created only once [13-16].

The research activities presented in this paper, developed in collaboration between the Queen's University Belfast and the University of Naples Federico II, concern the design and efficient configuration of the assembly line dedicated to the production of a Skycar light aircraft [17].

In this case study, the aircraft assembly cycle is designed in the virtual environment through the employment of different methodologies such as line balancing and cellular manufacturing [18]. Digital simulation is employed to evaluate and compare different scenarios with the aim to improve the resource efficiency of the line [19-20]. Assembly automation and optimization solutions are investigated with the aim to improve the resource efficiency of the assembly line, so as to reduce assembly costs and time [21-22].

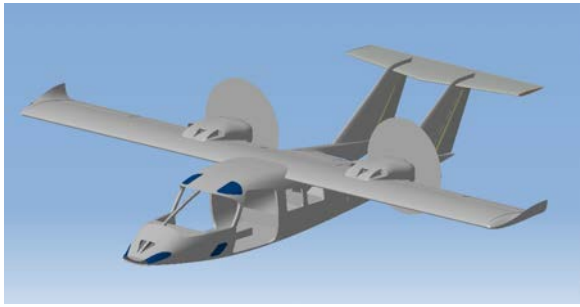


Fig. 1. 3D model of the Skycar light aircraft.

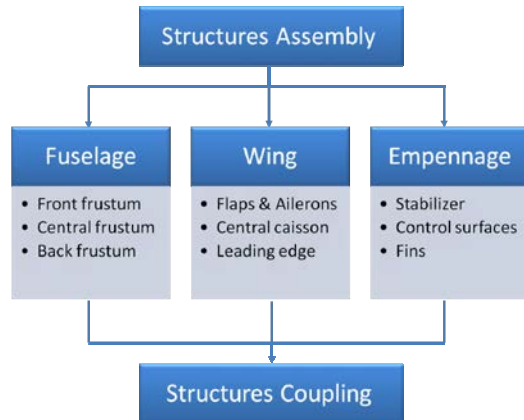


Fig. 2. The structures assembly of the Skycar light aircraft.

2. Definition of the assembly process case study

The case study examined in this paper concerned the configuration of the assembly line for the production of a Skycar light aircraft (Fig. 1) [17].

The aircraft consists of three main sub-assembly groups: fuselage, wing and empennage. These groups can be further sub-divided into nine sub-assemblies which have to be coupled together to produce the final aircraft, as shown in the scheme of Fig. 2.

2.1. Planning of the assembly sequence

As a starting point for the process planning stage, each of the nine sub-assemblies was assumed to be manufactured in separate sub-assembly lines and then delivered to the final assembly line, according to the layout reported in Fig. 3.

The following order for the final assembly was assumed:

- Front frustum to central frustum to create the fuselage
- Left tail and right tail to fuselage to finish the main body
- Wing to main body
- Fins, rudder and horizontal stabilizer to main body
- Flaps, ailerons and nacelle to wing
- Final fitting (including landing gear, engines and interiors)

The starting process plan could be further optimized, e.g. by re-designing the assembly process under DFMA principles.

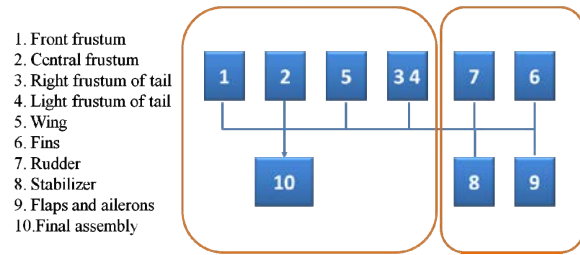


Fig. 3. The assembly layout for the Skycar light aircraft.

2.2. Estimation of the manufacturing times

With the aim to design the assembly line in a digital environment, the first step was to calculate the manufacturing times to be fed to the simulation model. An approach based on the combination of the methodology proposed in [23] and parametric costing model was adopted: this approach allowed to calculate the times in reverse starting from the cost. By knowing the cost of the aircraft and assuming the labor cost of a factory, an estimate of the overall manufacturing cost per unit aircraft was obtained through the following equation [23]:

$$AEP = \frac{(C_{MAN} + C_{PRO} + C_{RDTE})}{N_M} \quad (1)$$

Where AEP is the unit price of the aircraft, C_{MAN} the manufacturing cost, C_{PRO} the manufacturer's profit, C_{RDTE} the research, development, test and evaluation cost, and N_M the number of manufactured aircrafts. Estimations of the unit price and the potential profit were used, while N_M was set to 1.

The overall manufacturing cost (€681,818.18) was split and assigned to the different subassembly lines following the parametric costing approach, i.e. according to the respective weight fraction of each subassembly. For example, as the wing represented 20% of the overall aircraft, 20% of the manufacturing cost was assigned to it. Additional information was gathered from the aerospace manufacturing industry and, by implementing the purchasing power parity index, an estimated cost per workstation for the assembly line was calculated to be €163/hour. This average hourly rate includes manual labour, utilities, waste, maintenance, etc. It was then possible to calculate the required manufacturing time for each of the sub-assemblies and the entire aircraft.

2.3. Identification of the precedence constraints

A high-level Gantt chart was developed to illustrate the precedence constraints that could delay the assembly line. Apart from the wing, requiring a longer manufacturing time, the majority of the sub-assemblies take the same amount of time to be completed. These sub-assemblies have no precedence constraints and they can all begin simultaneously; however, at high level, all the sub-assemblies should be completed to start the final assembly of the aircraft. This high level Gantt chart was the basis for the development of a more efficient and optimized assembly line and was a useful indicator to gain an initial understanding of the process flow and to locate the bottlenecks before running any simulation.

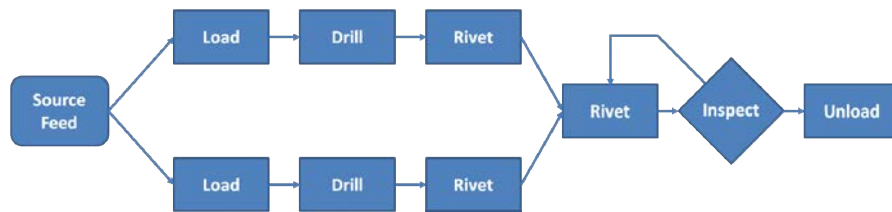


Fig. 4. Value stream map of the front frustum sub-assembly line.

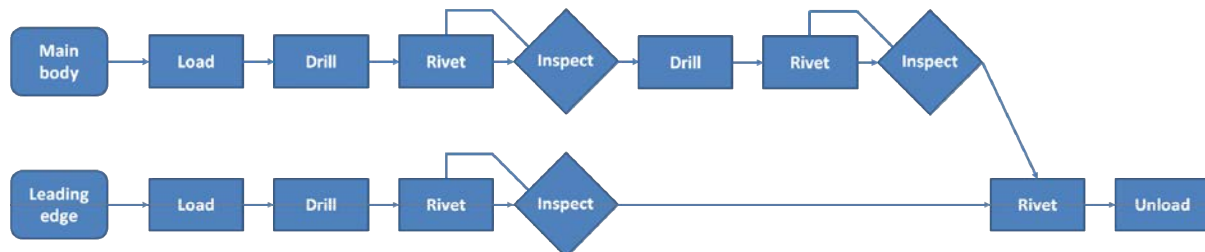


Fig. 5. Value stream map of the wing sub-assembly line.

3. Digital simulation of the assembly line

The approach proposed in this paper to support the design and the efficient configuration of the assembly line is based on the employment of digital simulation. In particular, discrete event simulation (DES) was adopted to simulate different scenarios and evaluate the performance of the assembly line [24]. An initial high-level DES model of the starting assembly line configuration was setup to evaluate the throughput and the efficiency of the line, and to suggest the potential improvements.

The model was setup by creating one station for each subassembly, and assuming that the final assembly starts only when all the sub-assembly processes have been completed.

The model was simulated by considering the availability of 1725 hours in one year. The resulting annual throughput was equal to 2 aircrafts, with the overall assembly line operating at a low efficiency of 17.4%. As during the simulation most of the work stations were in idle or blocked mode due to the line bottleneck, represented by the wing, further analysis of the assembly process was required to obtain more accurate information and improve the assembly process planning.

4. Optimization of the assembly sequence

4.1. Definition of the operations for each sub-assembly line

A more detailed and specified process sequence was required to include all the necessary assembly operations, details for the individual lines and a final cell layout developed in the DES model. The primary assembly sequence was decomposed into the following operations:

- Loading
- Drilling
- Riveting

- Inspecting
- Unloading

The process value map of the sub-assembly lines and the final assembly were developed according to this sequence. Hence, the sub-assembly lines were further detailed according to the DMFA approach: as an example, the value stream map of the front frustum and the wing subassembly lines can be seen in Fig. 4 and Fig. 5. As the front frustum is a symmetrical component, two parallel assembly lines were created, each assigned to half of the frustum, that eventually merge together to assemble the full front frustum. This design improvement would significantly reduce the assembly time.

4.2. Optimized assembly sequence

The percentage of time that each operation (loading, drilling, riveting, etc.) took was calculated and was used to further detail the process times for the Skycar assembly line.

A new scenario was assumed with the aim to optimize the assembly sequence and improve the resource efficiency of the overall assembly line. In this scenario, each subassembly was subdivided in its operations according to DFMA and value mapping. Moreover, instead of forcing the final assembly to wait for the completion of all the components, the assembly sequence was organized to reduce any potential block state. The proposed sequence for the final assembly is shown in Fig. 6, where the sub-assembly lines (1 - 9) are visible on the left side and the coupling sequences can be seen on the right. The new proposed layout allows several sub-assemblies to continue on to the final assembly without the need to wait that all the other sub-assemblies are ready. For example, front and central frustum can be coupled together while the wing is still being assembled. Similarly, left and right tail can be coupled to the fuselage without need to wait for other components. It is at this point where the final assembly station begins waiting due to the fact that the wing is next in line.

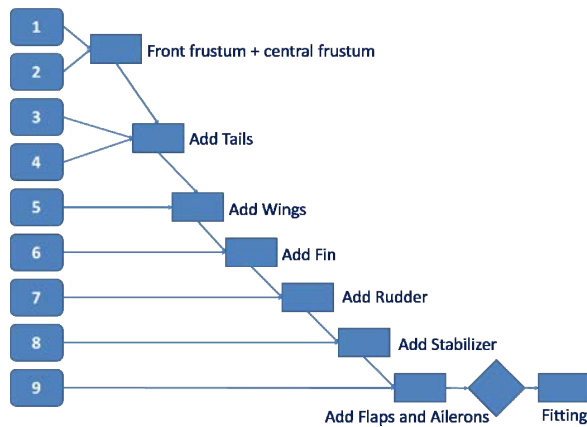


Fig. 6. Optimized final assembly sequence.

This new scenario, identified as scenario 2, was simulated and analyzed to obtain numerical results on performance indicators such as throughput, efficiency and throughput time, and to identify any potential bottleneck. Table 1 shows the performance indicators of the overall assembly line compared to the starting scenario. A noticeable increase was obtained in the percentage of working time of the subassemblies and a decrease in the amount of time they spent in blocked mode.

Table 1: Changes in the assembly line from Scenario 1 to Scenario 2.

	Scenario 1	Scenario 2	Difference
Throughput (units)	2	3	50 %
Efficiency (%)	17.4 %	26.1 %	50 %
Throughput time (hours)	2423.604	1382.87	42.9 %

The efficiency of the assembly line, equal to 26.1%, was still very low although being increased compared to the previous scenario. It was clear that the assembly line was not yet balanced and work stations were not used to their full potential. The opportunity for further optimization should be investigated through the adoption of different methodologies such as lean principles, line balancing techniques and automation of the assembly process.

5. Assembly line dimensioning and balancing

The primary objective of the optimization study was to increase the annual throughput to meet the annual demand. Once defined the annual throughput [25], equal to 26 aircraft units, assembly line dimensioning was carried out by determining the minimum number of workstations required to produce the given number of aircrafts.

The dimensioned assembly line could be then used as a basis for further improvement of time and efficiency through line balancing techniques.

To pursue this objective, the first step was represented by takt time calculation according to the equation below:

$$takt\ time = \frac{total\ time\ available / year}{number\ of\ units\ required / year} \quad (2)$$

The computed takt time (66.3 hours) was then used to calculate the minimum number of stations required for each process (loading, drilling, riveting, inspecting) as follows:

$$number\ of\ workstations = \frac{process\ cycle\ time}{takt\ time} \quad (3)$$

By summing up the number of workstations for each process, a total amount of 120 workstations for the entire assembly line was obtained: this number was input to the DES model with the aim to verify the capability of the assembly line to produce the required annual aircraft units and to evaluate its resource efficiency.

A long warm up time was required to prime the system, as long time taking operations are involved in the assembly sequence. The capability of the work stations increased dramatically. As all cells had the ability to produce the desired amount of sub-assemblies in the specified time, the throughput target could be met.

In particular, the resulting throughput was more than 26 units for some sub-assembly lines because their total manufacturing time per workstation is less than the takt time of 66.3 hours. For example, the subassembly line 7, which has a total manufacturing time of 38.9 hours, had the capability to produce 45 rudders whereas subassembly line 5 can only produce 26 wings. However, with the correctly balanced line, where stations did not exceed the desired cycle time, there was a significant idle time. Fig. 7 shows the efficiency of the single subassembly lines. The overall efficiency of the assembly line was about 44.11 %.

5.1. Line balancing for resource efficiency improvement

The previous simulation model assessed that the proposed assembly line configuration is able to produce the required annual volume of products. However, the statistics concerning the utilization of the single workstations show that some of them are very low utilized. Therefore, further line balancing was implemented to increase the efficiency of the assembly line. In particular, in the previous scenario, it was assumed that a dedicated operator was assigned to each station. However, a long idle time was noticed in the simulation results, suggesting that the number of operators could be reduced by assigning tasks in a more efficient way.

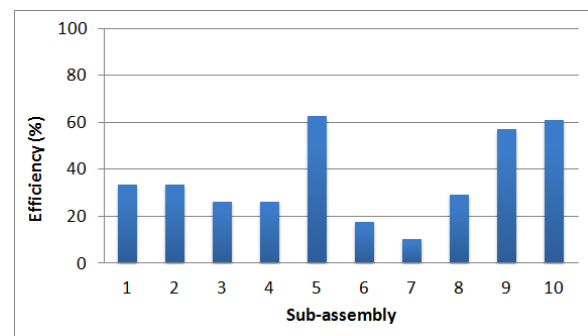


Fig. 7. Utilization of resources of the subassembly lines in scenario 3.

To improve the efficiency, a single operator was therefore assigned to subsequent operations such as load, drill and rivet, until the sum of their cycle times reaches the takt time.

As different operations are grouped and carried out by only one labor, the number of operators is much decreased compared to the previous 120 units. The calculations indicated a new number of labors equal to 62 units, meaning that the manning level was almost decreased by 50%. This new scenario, indicated as Scenario 4, was simulated in DES and the results in terms of utilization of resources, in particular labors, show a much increased efficiency of the labors and consequently increased efficiency of the overall assembly line from 44.11% to 83.23%.

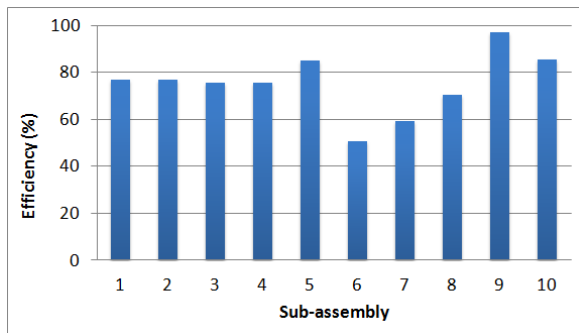


Fig. 8. Utilization of resources of the subassembly lines in scenario 4.

5.2. Automation of the loading process

In the original case study, the entire assembly process was carried out manually. Further analysis was therefore carried out to verify whether slow and costly manual operations could be replaced by semi-automatic processes. By examining the entire assembly line, it was easily noticed that the final assembly station represented the main bottleneck of the system. As a matter of fact, once all sub-assemblies have been manufactured, 1172 hours are still required to go through all the final assembly workstations to complete an aircraft. The majority of this time is related to the long process of loading the sub-assemblies onto the assembly jigs, contributing for 63% of the time. Therefore, a new scenario was assumed for the assembly line. Following the example of an already existing project carried out for the installment of positioning and alignment machines for the Boeing 787 Dreamliner [30], an automated loading system was introduced in the assembly line to carry out the loading of the final assembly. The work illustrated in [30] outlined that the time savings coming from the loading automation was approximately 37%. These statistics were then incorporated into the final assembly station for the Skycar light aircraft and a new model was setup and simulated in the DES software. The number of required workstations was decreased by 4.84% compared to scenario 4, going from 62 to 59 units. The numerical results concerning the performance indicators of the assembly line are reported in Table 4. As it can be observed, the simulation run resulted in a lower efficiency of 74.37%; however, 27 aircrafts were produced instead of 26 units, and a 10% reduction in the throughput time from 1508 to 1354.25 hours was achieved.

5.3. Cellular manufacturing

To deal with the remaining inefficiencies of the assembly line, a cellular manufacturing approach was adopted. In particular, subassemblies 6, 7 and 8 were operating at 50.5%, 59.1% and 70.4% efficiencies respectively (Table 2). As these three stations were meant to manufacture three similar sized components, each being part of the empennage assembly, cellular manufacturing could enhance their productivity.

Cellular manufacturing is based on the so-called “group technology” and minimizes the disadvantages of batch production by recognizing that, although parts are different, there are families of parts that possess similarities. When these similarities are exploited in production by using work cells, operating efficiencies are improved [31].

Station 6 and 8 consisted of 2 cells and subassembly 7 consisted of 1 cell. The individual cells were analysed as concerns the time distribution within the cells and their efficiency. A new mixed model configuration employing 4 cells instead of the initial 5 cells and grouping the operations carried out on the three different assembly lines was designed based on cellular manufacturing approach, as shown in Table 2 and Table 3.

The new scenario, identified as scenario 6, including the new mixed model station incorporating all the processes for the three subassemblies, was simulated and resulted in an increased total efficiency of 78.51%.

The number of workstations required in the assembly cell was decreased from 59 to 58 units, while keeping the same performance in terms of throughput time (1354.25 hours) and annual volume produced (27 units).

Table 2. Breakdown of processing times (hours) and efficiency of the single stations for subassemblies 6, 7 and 8.

Single station	Cell 1 (hours)	Cell 2 (hours)	Efficiency (%)
Subassembly 6	61.61	5.23	50.5
Subassembly 7	38.99	-	59.1
Subassembly 8	59.129	33.78121	70.4

Table 3. Breakdown of processing times (hours) and number of workstations required for the mixed model station.

Mixed model station	Cell 1	Cell 2
Workgroup load (hours)	159.19	39.02
No. of workstations required	2.40	0.59
No. of workstations required (integer)	3	1

Table 4. Throughput, efficiency and throughput time of the assembly line in the different simulated scenarios.

	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Throughput (units)	26	26	27	27
Efficiency (%)	44.11 %	83.23 %	74.37%	78.51%
Throughput time (hours)	1508.17	1508.17	1354.25	1354.25
No. of workstations	120	62	59	58

6. Conclusions

This paper presented research activities related to the definition and optimal configuration of an assembly line for the realization of a Skycar light aircraft. The analysis of the product structure was carried out to design and specify an appropriate assembly line taking into account DFMA principles and value map processing techniques to define the sequence of operations.

An initial assembly line configuration was proposed and verified using discrete event simulation to examine performance indicators such as throughput, efficiency and throughput time.

The discrete event model of the assembly line was fed with increasingly detailed input information, to accurately simulate the line behavior in the digital environment until and identify any potential areas for optimization such as bottlenecks and low efficiency work stations. Optimization methodologies based on line balancing, automation of the loading processes and cellular manufacturing were then implemented into this proposed assembly configuration with the aim to improve its resource efficiency, reduce the throughput time and the number of workstations in the line.

The iterative process resulted in a final assembly line configuration capable to produce the desired throughput of aircrafts/year with an overall efficiency of more than 78.51%.

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