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A geometrical model for managing Surface Productivity of U-Shaped Assembly Lines

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U-Shaped Assembly Lines (U-SALs) are cellular manufacturing systems that, among other things, provide a remarkable feature for industrial cost efficiency: their effectiveness in space utilization. While the challenge of machine placement for labour productivity optimization is widely studied in the literature, surface productivity optimization has been scarcely explored. This paper proposes an industry-validated geometrical model for optimizing U-SAL surface productivity. The model links the drivers for market, product and process with the geometrical design. Managers and lean practitioners can use this approach to make decisions for layout design. The model is particularly useful in cases where the cost of floor space is substantially high.

Assembly, Productivity, U-shaped line

1. Introduction

In the last ten to fifteen years, as markets are becoming more competitive and the production paradigm has shifted from mass production to mass customization, manufacturers are increasingly accommodating mixed-model assembly lines [1,2] with a particular focus on U-Shaped Assembly Lines (U-SALs). Space optimization is becoming more and more important in this context, especially for companies that are either located in places where the cost of floor space is substantially high or that are willing to expand or update their manufacturing activity with new products that require new production capabilities and floor space. Thus, there exists a growing body of academic research exploring various facets of U-SAL design. Most of this research is focused on labour productivity. Although it is a key topic, increasing efforts toward European reindustrialization need new perspectives on productivity from a systemic point of view, in particular: surface productivity. This research induces a model to optimize U-SAL surface productivity from a multiple-case-study analysis of industrial firms.

2. U-Shaped assembly lines in literature

The Toyota Production System (TPS) was developed in Japan after 1945 as an alternative to Mass Production Systems. Taiichi Ohno (recognized as the founder of TPS) stated in an early English translation from 1978 [3]: '*In 1947, machines were arranged in the shape of the character '='' [...] one operator using three machines*'. This is the first mention of the so-called 'U-Shaped Lines', a manufacturing solution for lead time reduction and cost optimization when labour costs are higher than machine amortization.

According to Miltenburg [4], the term 'U-shaped' was used for the first time in 1982 by Schonberger [5] to refer to this particular topography. He remarked the benefits in both flexibility and labour productivity. In 1983, Hall [6] mentioned 'U-shaped layout' and 'U-lines' again. Also, in 1983 Monden [7] dedicated a chapter to describing U-shaped lines as a key factor of the TPS. Monden [7] highlights *Shojinka*, meaning a flexible manpower line whose 'most remarkable advantage' is its ability to be adjusted to meet production requirements with any number of workers and changes in demand. In 1990, 'Lean Production' was introduced by Womack et al. [8] as a generic denomination for TPS. They mentioned, for the first time, the idea of surface utilization along with some other basic metrics to analyse assembly lines.

Hereafter, the analysis of surface utilization was however set aside in the research literature and the main focus turned towards increasing productivity: in 1992, Sekine [9] used the term 'U-shaped cells' and he detailed how to design them with the objective of shortening lead time and improving productivity; in 1994, Miltenburg and Wijngaard [10] introduced the U-Line Balancing (ULB) problem and showed how a U-line has much more balancing possibilities than I-lines; in 2004, Aase et al. [11] established some factors that make U-SALs more productive than their equivalent I-SALs, those factors being: higher network density, a lower number of assembly tasks and a shorter cycle time. In 2006, Kumar and Matho [12] provided an extensive literature analysis on assembly line balancing problems and formulations. In relation to ULB, they found that minimizing the number of workstations and maximizing the production rate were the commonly used objectives of the methods reviewed, with no mention being made of surface productivity as a relevant parameter.

More recent literature adds other objectives to the traditional workstation minimization problem, such as studies on the optimal operations of robots in workstations [13] and how to enable the collaboration of humans and robots on assembly lines [14,15], and the design of cells that can be optimally reconfigured [16,17]. More recent work addresses the ULB problem again but from other perspectives; e.g., Oksuz et al. [18] solved the ULB problem by also considering the worker performance. Optimization methods such as genetic algorithms have also been applied in recent years for either U-SAL balancing [19] or for optimizing the design of material handling systems of lean automation lines [20].

In summary, U-SALs have been part of the TPS since its foundation, and they are the ideal layout for ‘one-piece-flow’ to minimize waste in assembly processes. Their relevant advantages are:

1. Lead time reduction.
2. High levels of labour productivity due to:
   - Avoiding operator wait time for machines.
   - Multiplying balancing possibilities.
3. Adaptability (*Shojinka*): throughput variation by adding or removing operators inside the U space.
4. Very efficient surface utilization due to:
   - Work in process elimination.
   - Workstations and machines placed close together.

As can be seen from the presented literature review, the U-SAL optimization problem has once again become a relevant research topic. However, most scientific studies, even those published after 2016 [21,22], focus mainly on workstation minimization, on lead time reduction and on labour productivity optimization, as Miltenburg and Wijngaard [10] stated in their ULB problem. Although labor productivity is a relevant topic, the increasing implementation of U-SALs in manufacturing facilities requires new perspectives of productivity from a systemic point of view.

In this context, this paper presents a U-SAL surface productivity management and optimization method, which is particularly relevant nowadays for many industries located where the cost of floor space is substantially high or where surface constraints limit the possibilities of spatial growth for factories that seek to expand their manufacturing capabilities.

This study is based on an inductive approach. The determination of the analytic model is based on the modelling approached designed in [23]. To this end, a multiple case study analysis has been carried out with industry-validated solutions, which have been selected as successful cases in their respective factories due to their optimal use of space in obtaining high productivity.

3. Field study

To conduct a systematic observation, the following parameters have been measured and calculated for each case study:

- Q = Maximum throughput (units per hour: u/h)
- N = Number of workstations (-)
- S = Total surface without aisles (m^2)
- S_u = Surface of the product (m^2)

From these parameters different ratios have been calculated in order to characterise each U-SAL in terms of surface usage. These ratios are defined in Table 1. Tables 2 to 6 show the values for both the parameters and the ratios of five different U-SALs used to assemble five different products of relatively small sizes and short single assembly tasks.

Table 1. Ratio definitions for cross-case analysis of surface use.

Ratio	Meaning
$SP=Q/S$ [8]	Efficiency in the use of the surface (surface productivity) in units/hour/m^2 (u/h/m^2).
$WS=S/N$	Compaction of workstations (m^2).
$WS_u=S/S_u$	Number of products that can be placed on the U-SAL surface (-).

Table 2. Case 1: characterisation of printer carriage U-SAL.

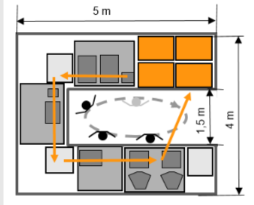
TOPOGRAPHY	Data	Value	Comments
	Q	60u/h	Manual assembly
	S	20.0m^2	
	N	3	
	S_u	0.03 m^2	
	SP	3.0 u/h/m^2	
	WS	6.7 m^2	
	WS_u	667	

Table 3. Case 2: characterisation of car light U-SAL.

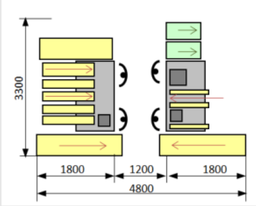
TOPOGRAPHY	Data	Value	Comments
	Q	120 u/h	Manual assembly with soft automation
	S	15.8 m^2	
	N	4	
	S_u	0.09 m^2	
	SP	7.5 u/h/m^2	
	WS	3.9 m^2	
	WS_u	176	

Table 4. Case 3: characterisation of engine filter U-SAL.

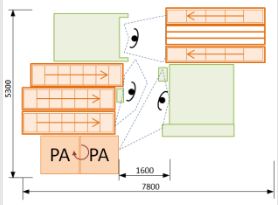
TOPOGRAPHY	Data	Value	Comments
	Q	110 u/h	Semi-automated assembly with large welding machine
	S	41.4 m^2	
	N	3	
	S_u	0.12 m^2	
	SP	2.7 u/h/m^2	
	WS	13.8 m^2	
	WS_u	335	

Table 5. Case 4: characterisation of car exhaust pipe U-SAL.

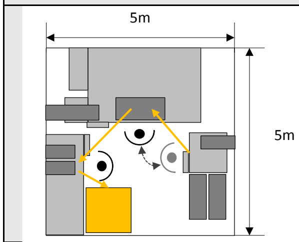
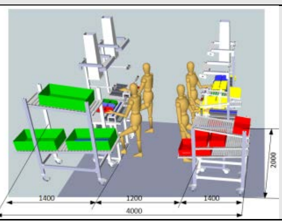
TOPOGRAPHY	Data	Value	Comments
	Q	25 u/h	Manual assembly plus automatic welding
	S	25.0 m^2	
	N	2	
	S_u	0.12 m^2	
	SP	1.0 u/h/m^2	
	WS	12.5 m^2	
	WS_u	208	

Table 6. Case 5: characterisation of light sabre toy U-SAL

TOPOGRAPHY	Data	Value	Comments
	Q	15 u/h	Manual assembly
	S	8.0 m^2	
	N	4	
	S_u	0.10 m^2	
	SP	1.9 u/h/m^2	
	WS	2.0 m^2	
	WS_u	80	

By comparing the ratios (Table 7), the best solutions have been identified and analysed in order to find the key factors for their high performance. The best values are in bold in Table 7.

Table 7. Ratio results for the industry study cases.

Case	SP	WS	WS_u
1- Printer carriage	3.0	6.7	667
2- Car light	**7.5**	**3.9**	**176**
3- Engine filter	2.7	13.8	335
4- Car exhaustion pipe	1.0	12.5	208
5- Light sabre	1.9	**2.0**	**80**

In terms of compaction of the space (*WS*), the best ratios are obtained in cases 2 and 5, where the smallest values are found. Therefore, the U-SALs of cases 2 and 5 demonstrate good topography in the sense of not being a ‘U’, but an ‘=‘; i.e., two parallel lines without a third side closing the ‘U’.

In terms of the efficiency of surface usage or surface productivity, high values of *SP* are expected as well. In case 2, the highest value of *SP* can be found. This means that less time to assemble one unit is required. From this correlation, it can be inferred that product assembly time is one of the factors that determines surface requirements, as it influences the number of workstations.

Product size is another factor that could influence surface. WS_u measures how compact the solution is in relation to product surface. Therefore, low values for this ratio are sought. Again, cases 2 and 5 show better results due to their ‘=’ topographies.

Case 3 also has an ‘=’ topography similar to those of cases 2 and 5, but its *WS* and WS_u ratios are worse. The reason for this is the large size of the machinery needed in case 3, as well as the large amount and size of materials stored in the cell. From these observations, it can be inferred that the supply process also influences the required space, as the supply process determines the amount of stored materials in the U-SAL.

4. General model definition

Three main elements influence the surface needed in a U-SAL: people (ergonomic space), workstations (machinery) and materials. These elements are determined by market, product and process requirements (see Table 8).

Table 8. Factors influencing surface needs.

	Factor	Connection and notation
Market	Customer demand	Customer Demand (D) sets the Takt Time (TT) that influences the Throughput (Q).
Product	Complexity	Defines the Manual Assembly Time (T_{ma}). Defines the number of components to be stored in the workstation.
	Size	Defines the minimum workstation surface for handling the product.
Process	Technology	Defines the machinery size. Defines the Automatic Assembly Time (T_{au}).
	Supply process	Defines the Fulfilment Cycle (C_f) and, thus, the quantity of components at the workstation.
	Production process	Defines the Throughput (Q) and Cycle Time (T_C).

Some design factors have been simplified by choosing the best-case possibility in terms of surface reduction. This ‘as good as it gets’ (AGAIG) criterion has reduced the model’s complexity.

The U-SAL topographies can be generally characterised by the geometrical configuration shown in Fig. 1.

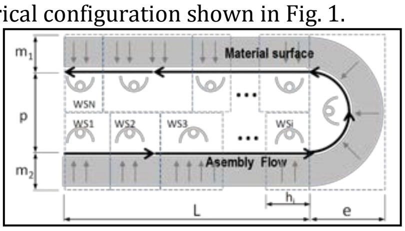


Figure 1. General topography for a U-SAL with *N* workstations.

In addition, with the AGAIG criterion, the workstation width, h_i, cannot be less than the ergonomic space needed for a standard person, *h*. This is a realistic situation for a wide range of cases with the following characteristics:

(a) Product size does not influence h_i.
(b) Quantity and dimensions of parts do not influence h_i.
(c) Machine and tooling processes do not influence h_i.

Thus, a more compact topography can be defined by the shape of the character ‘=’, as described by Ohno [3] and also concluded from the cases studied in Section 3.

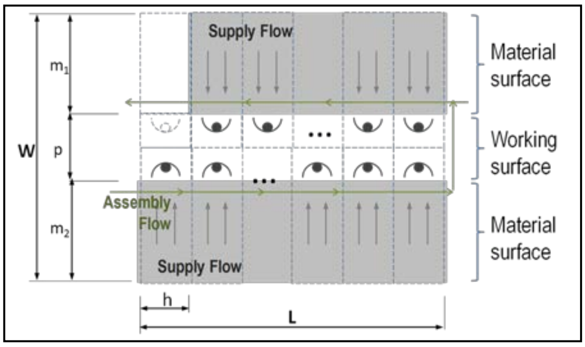


Figure 2. AGAIG topography for a number *N* of workstations.

Surface Productivity (*SP*) is defined as the ratio between Throughput (*Q*) and Surface (*S*) to meet this throughput.

$$SP = \frac{Q}{S} \text{ where } Q = \frac{1}{T_c} \text{ and } S = W \cdot L \rightarrow SP = \frac{1}{T_c \cdot W \cdot L} \quad (1)$$

If *h* is the same for all workstations, then U-SAL length (*L*) is:

$$L = \left\lceil \frac{N}{2} \right\rceil \cdot h \quad (2)$$

where *N* is the total number of workstations. With the AGAIG criterion, *N* is minimum if a perfect split of assembly tasks among the workstations is possible and operators never have to wait for the machine. In this situation:

$$N = \left\lceil \frac{T_{ma}}{T_c} \right\rceil \Rightarrow L = \left\lceil \frac{\left\lceil \frac{T_{ma}}{T_c} \right\rceil}{2} \right\rceil \cdot h \Rightarrow L = \left\lceil \frac{T_{ma}}{2 \cdot T_c} \right\rceil . h \quad (3)$$

The U-SAL width *W* is defined as:

$$W = p + m_1 + m_2 \quad (4)$$

where m_1 and m_2 are determined by the quantity of the worst part (*WP*) in terms of surface occupation at the workstation. Considering the worst part on each side of the U-SAL, a density factor can be defined as:

$$\alpha_1 = \frac{m_1}{WP_1};\ \alpha_2 = \frac{m_2}{WP_2} \quad (5)$$

The number of parts stored at the workstations must be at least enough to cover the Fulfilment Cycle (C_f); otherwise, the U-SAL stops. So, the number of each part to be stored is:

$$Parts_i = \frac{C_f}{T_c} \cdot n_i \quad (6)$$

where n_i is the number of $Part_i$ per product.

In particular, considering the worst part as described:

$$m_1 + m_2 = \alpha_1 \cdot n_1 \cdot \frac{C_f}{T_c} + \alpha_2 \cdot n_2 \cdot \frac{C_f}{T_c} = (\alpha \cdot n_1 + \alpha_2 \cdot n_2 \cdot) \cdot \frac{C_f}{T_c}$$

$$\Rightarrow W = p + \delta \frac{C_f}{T_c} \quad (7)$$

where $\delta = (\alpha \cdot n_1 + \alpha_2 \cdot n_2)$ is a density factor defined by the shape of the worst parts and how they can be compacted inside containers.

Therefore, the total surface can be determined as

$$S = \left(p + \delta \cdot \frac{C_f}{T_c}\right) \cdot \left\lceil \frac{T_{ma}}{2 \cdot T_c} \right\rceil \cdot h = \left(p + \delta \cdot C_f \cdot Q\right) \cdot \left\lceil \frac{T_{ma} \cdot Q}{2} \right\rceil \quad (8)$$

and thus the surface productivity can be formulated as:

$$SP = \frac{1}{S \cdot T_c} = \frac{1}{\left(p + \delta \frac{C_f}{T_c}\right) \cdot \left\lceil \frac{T_{ma}}{2 \cdot T_c} \right\rceil \cdot h} \quad (9)$$

By applying this mathematical model to typical values in industry, Fig. 3 shows the evolution of surface to throughput and surface productivity to cycle time in a graphical way.

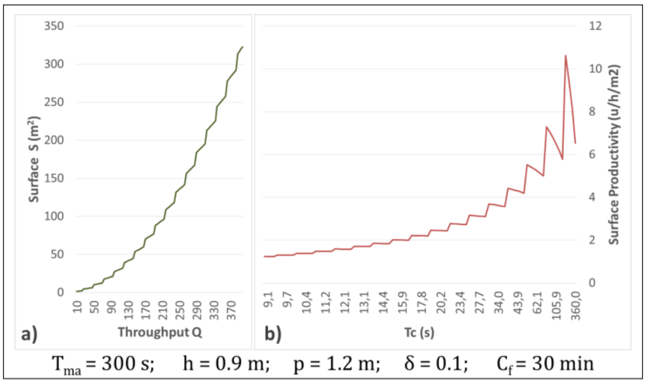


Figure 3. For typical industrial values: a) Surface (S) vs. Throughput (Q); b) Surface Productivity (SP) vs. Cycle Time (T_c).

5. Discussion

The presented model supports the following new findings:

- Surface needs have a quadratic relationship with throughput, which can be derived from Eq. (8).
- Once the cycle time is defined, the length is set and the width is only proportional to the fulfilment cycle. By doing so, surface needs can be easily managed.
- There is no single optimum for surface productivity in relation to the cycle time, which makes cycle time an independent variable in such types of decisions.
- There are, however, some cycle times that maximize surface productivity locally (see Fig. 3b).

In a lean production system context, one of the most important principles is to 'produce accordingly to customer takt time'. This means that in an ideal situation: $T_c = TT$. However, in a more realistic way: $T_c < TT$ or $Q > D$.

Once the takt time is set and the product and parts are well defined for complexity and size, the proposed model guides the decision-making process about surface optimization as follows:

First: As the surface has a quadratic relationship with the throughput, setting up several U-SALs is more efficient than only one. This is particularly important when the cycle time is much less than the manual assembly time (Eq.8). Notice that this decision has an impact on capital investment.

Second: Once a decision on the number of U-SALs is made, the cycle time can be fine-tuned in order to locally maximize the surface productivity.

Third: If there are strong surface constraints, the fulfilment cycle can be reduced, lowering m_1 and m_2, and consequently reducing the surface requirements (see Fig.2). Notice that, with such a systemic view, this option has a direct impact on the effectiveness of the fulfilment process.

6. Conclusions and future research

This research examined surface productivity of U-SALs. Departing from five industry-validated U-SALs, the cross-case analysis showed that 1) better solutions regarding surface productivity are found when workstations are arranged in two parallel lines like an "=" without a third side closing the "U", 2) product assembly time determines the surface requirements as it influences the number of workstations, 3) the supply process also influences the required space, as the fulfilment cycle determines the number of materials stored in the U-SALs.

Considering the field study conclusions a geometrical model for managing and optimizing surface productivity in U-SALs has been defined. The proposed geometrical model integrates multiple factors, including market, product and process factors to guide the final layout design of U-SALs. Some simplifications have been introduced, which are particularly realistic for small products with short single assembly tasks. The model sets the surface requirements based on three main variables: throughput, cycle time and fulfilment cycle. In all cases, the model calculates an 'as good as it gets' surface requirement, which is very useful during layout design and optimization.

This paper also leaves some open questions that need further research:

- If the produced parts are large or numerous and the quantity of workstations are below a certain number, the workstation width (h_i) increases. This means that $h_i = f(N)$ must be considered.
- There should be further analysis of how the fulfilment cycle impacts the dimensions of aisles and, consequently, surface productivity.
- Studies could be developed on potential optimal supply cycle which might maximize logistics productivity.
- A model for a plant layout based on U-SAL and milk run circuits that optimize surface productivity could be proposed.

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