Ergonomic evaluation of a hybrid U-shaped assembly system

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Abstract: In practice, U-shaped assembly systems often prove more advantageous in comparison to straight-line systems. This is mainly due to their possibilities regarding production logistics and associated staff. Accordingly, such systems are usually evaluated in the planning stage using production logistics and cost-oriented criteria. However there are also possible ergonomic drawbacks. Therefore, it is necessary to complete the evaluation of these systems based on ergonomic criteria. In this way, unfavourable forms of work organization can be identified in the planning stage. It also appears that the static methods used for planning are not suitable because of their overly optimistic results, and therefore a dynamic safeguarding must be complemented by the simulation. In this way, it is first possible to ascertain whether the anticipated production logistic objectives can be achieved. In addition, the simulation then provides more realistic evidence on ergonomic criteria. This article describes the ergonomic and production logistics evaluation of a hybrid U-shaped assembly system with model-mix program.

Practitioner Summary: In the context of production logistics, U-shaped assembly systems often present several advantages compared to straight-line systems. Therefore, such systems are usually evaluated in the planning stage using production logistics and cost-related criteria. However, some published papers illustrate that these advantages may face ergonomic drawbacks. The evaluation must therefore be expanded in order to evaluate these systems from an ergonomic perspective. In this way, unfavourable forms of work organization can be detected already during the planning stage. In addition, the static methods generally used for planning prove to be poorly applicable due to the overly optimistic results they generate. Consequently, the solutions must be validated dynamically by means of simulation. Only then can be judged whether the planned production logistics criteria are achievable at all. In addition, the simulation allows more realistic statements concerning ergonomic criteria.

Keywords: assembly planning, U-shaped layout, walkways, travel times, energy expenditure

1. Advantages of U-shaped assembly systems over assembly lines
1.1 Advantages in terms of production logistics

In recent years, U-shaped assembly systems have been increasingly used for low-volume products in particular. These have, compared to straight-line systems, some advantages in terms of production logistics (see e.g. Hrdina et al. 2013): Input and output stations are located on the same narrow side of the system, which allows the input components and the final product to be delivered at the same side. In addition, the supply of further material can take place from the outer sides of the assembly system, while the staff are active on the inner sides. Furthermore, the number of employees can be varied depending on the number of product units to be assembled per shift.

Often U-shaped assembly systems have manual, mechanized and automated operations. There are so-called hybrid systems in which fewer employees are deployed than stations. Such assembly systems are sometimes referred to as Chaku-Chaku lines. U-shaped assembly systems allow different forms of work organization: assignment of staff to adjacent and opposing stations, variations thereof, and associated one-piece flow staff deployment. This of course assumes that employees have the necessary qualifications and training.

Within the framework of a planning project, it is necessary to clarify which form of work organization should be chosen under production logistics and cost-related criteria. The important production logistics evaluation criteria are: the output per unit of time, the throughput time of the products as well as the...
utilization of the stations and staff. Collaboration with experts in the company for time studies is necessary in order to determine these planning data.

1.2 Possible ergonomic disadvantages and criteria

Beyond the advantages related to production logistics of U-shaped over straight-line assembly systems, there are also some ergonomic disadvantages. For example, Enriquez Diaz et al. (2010) have indicated the need for ergonomic analysis of product flow accompanying staff deployment. Ergonomic aspects should also be taken into account when planning, so that subsequent investment for ergonomic adjustments in the realized assembly system can be avoided.

In principle, straight-line and U-shaped assembly systems can be ergonomically evaluated with the same criteria. A new focus is placed on such projects from an ergonomic perspective: the task is to introduce the evaluation criteria into the project in a formalized, verifiable form.

Although the staff stress through work content is often negligible because of the low product weights and volumes, and the stress through work environment can be minimized in most cases by appropriate design measures. But, the stress through standing posture and by rotation across several stations must be considered in more detail. In contrast, as a result of the generally relatively low weight of the work objects and tools, and the extensive mechanization and automation of technical equipment, applied forces and torques can often be dispensed with as an evaluation criterion.

In addition to the utilization of staff, the metabolic energy expenditure per shift is significant. Furthermore, criteria such as the length of the necessary travel distances, the travel time and the relationship between travel times and manual operation times come into focus. The distance to be travelled by staff may be less with multi-station operations at U-shaped assembly systems than with straight assembly lines, but due to short cycle times a substantial workload can also be the case. In addition, appropriate work areas and walkways must be available (see the German guidelines ASR A1.2, 2013, and ASR A1.8, 2012).

Not only are the mean values to be determined with the ergonomic criteria, but also their dispersions. Higher values of the dispersion indicate a non-uniformity, which can be perceived by the working group as unequal distribution of work. The relative mean difference (see Clauß et al. 2012, p. 39) is used here as a measure of dispersion, because of the relatively small number of employees.

2. Static and dynamic planning of U-shaped assembly systems

For these ergonomic, production logistics and cost-related considerations static and dynamic planning methods come into play. Subsequently, only the first two categories are considered here in the evaluation and assessment of possible planning alternatives.

Figure 1: Modeling of parts production and assembly systems using precedence graph, capacity graph and staff assignment graph (see also Zülch et al. 2011).
2.1 Static planning of the assembly system

The first planning phase of a hybrid, U-shaped assembly system includes the mapping of the assembly operations on the stations of the work system (Figure 1). The assembly operation may take the form of a precedence graph (Prenting und Bataglin 1964), while the stations take a capacity graph form (see for the first time Dittmayer 1981). Thus, this first phase can be interpreted as a mapping of a precedence graph on a capacity graph (see also Zülch and Zülch 2014a).

This first planning phase is referred to as line balancing of the assembly system. The result is the cycle time of the system and the number of required stations. For this planning phase, the same methods of Operations Research can, in principle, be used in the case of a U-shaped assembly system as in that of straight-line systems (see for a summary Zülch and Zülch 2014b, p. 2181). The significant input variables of the planning include the number of products to be assembled per shift, and the required operation times. The virtual result in both cases is a sequence of serially connected stations.

In the case of a model-mix program, the volume-weighted average of the operating times is used for the product types to be assembled. Some methods allow the use of stochastically distributed operation times (such as Kara and Tekin 2009), while others consider the travel times of the employees. Since this is a relatively small example in the present case, a spreadsheet calculation for the Ranked Positional Weight method by Prenting and Battaglin (1964) is used.

In the next planning phase, the staff structure has to be determined by the number and qualifications of employees. The latter is obtained for an employee from the operations at those stations to which the employee is assigned. This results in the allocation of staff to assembly stations, which is the mapping of the capacity graph to a staff assignment graph. As mentioned above, different forms of work organization may be developed, which can then be subjected to evaluation.

However, special methods are required for the derivation of the staff assignment graph in a U-shaped assembly system, which differ according to the restrictions taken into consideration. Below, the approach of the Phantom Graph is used according to Urban (1998).

The methods mentioned, however, result in static solutions: The interaction between employees and stations, and the possible resulting bottleneck situations cannot be detected in this way, especially in a model-mix assembly system.

Furthermore, for all procedures line balancing of the assembly systems takes only one resource type into account: either, assuming that the employees do not create a bottleneck, the precedence graph is mapped on the capacity graph, or the precedence graph is mapped directly on the staff assignment graph. The latter is equivalent to the assumption that the human activities are determinative.

These static methods use only a single objective function. Hybrid assembly systems in which the manual operation times are shorter than the station times are not taken into account in the literature, to the knowledge of the author (for an exception see Zülch and Zülch 2014b).

2.2 Dynamic planning of the assembly system

To check the dynamic behaviour of a hybrid U-shaped assembly system with model-mix program a suitable simulation procedure must be used. In this way, the simulation method replaces the "objective function", usually using multiple objectives with logistical and possibly also cost-oriented criteria. Of these, subsequently only the production logistics aspects are considered.

However, a staff-oriented simulation method (see the definition in VDI 3633, part 6, 2001) is required for this planning phase. For example, the simulation procedure FEMOS can be used, which was developed at the Ifab-Institute of Human and Industrial Engineering at the Karlsruhe Institute of Technology, in Germany. FEMOS is a German acronym that stands for "Fertigungs- und Montagesimulator", which translates as "manufacturing and assembly simulator" (see for the first time Grobel 1992, pp. 25). FEMOS is an event-driven, time-discrete simulation procedure that can model operating resources and staff independently from each other. The connection between the two is the modelled operation that equally needs both types of resources. This includes different operation times for both employees and stations for the execution of an operation. Due to the existing literature on this simulation procedure, a more detailed description can be omitted here (see e.g., Zülch and Grobel 1996).
2.3 Ex-post evaluation of ergonomic criteria

Besides the usual production logistics criteria such as production output, product throughput time as well as the utilization of staff and stations, ergonomic aspects can also be included in the evaluation. As one of its results the simulation provides the number of assembled products per shift, which in turn is connected with the operations performed by each employee. Therefore, there is an easy way to carry out the ergonomic evaluation based on an ex-post analysis following the simulation taking the number of executed operations into account.

Subsequently, the metabolic energy expenditure is used for the ergonomic evaluation. During the planning of an assembly system, this can be determined by the so-called group evaluation table by Spitzer et al. (1982, p. 143). In addition, the number of steps is calculated for each employee. This value is derived from a time evaluation according to MTM as a factor influencing the MTM code W-P[step]. A measure of dispersion is also calculated for these two ergonomic criteria in order to determine the non-uniformity within the working group in the system.

3. Case study for the planning and evaluation of a hybrid model-mix assembly system

Planning a hybrid model-mix assembly system in a U-shape should therefore take place in three phases: From mapping of the precedence graph of the assembly operations on a capacity graph of the stations, its mapping on the staff assignment graph of employees with the resulting number and qualifications, and further the simulation and its evaluation based on multiple criteria. This three-phase approach is illustrated below in terms of a production logistics and ergonomic evaluation using a case study.

3.1 Description of the planning problem

For this purpose, use is made of a hybrid model of Müller (2002, pp. 160), which is based on a simpler version by Buxey (1974) and augmenting it with a planning case with mixed assembly program (see also Zülch and Zülch 2014b, pp. 2184). The manual operation times are approximately one third of the station times, while the travel times include the necessary leg movements and body rotations which are achieved by means of MTM.

It is assumed here that the balancing of the assembly system has already been carried out by means of a spreadsheet (Table 1; symbols as per internationally available terminology according to REFA 2002). The result is a cycle time of 27 seconds, and 12 stations, one of which has two parallel work places.

Table 1. Station structure of the U-shaped model-mix assembly system.
Table 2. Alternatives for the personnel structure of the hybrid U-shaped assembly system.

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<tbody>
<tr>
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<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
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<tr>
<td>m [t/shift]</td>
<td>1</td>
<td>1,2</td>
<td>6,7</td>
<td>9,10,3</td>
<td>4,14,25</td>
<td>6,24</td>
<td>8,1213,16,24</td>
<td>11,15,17,18,20</td>
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<td>te [sec]</td>
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<td>500</td>
<td>9</td>
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<td>7</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<tr>
<td>(Anna) t [sec]</td>
<td>1,500</td>
<td>8,90</td>
<td>8,80</td>
<td>8,70</td>
<td>8,95</td>
<td>8,50</td>
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<td>Sum 1,000</td>
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<td>8,700</td>
<td>8,950</td>
<td>8,500</td>
<td>8,500</td>
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</table>

For a production logistics evaluation the following criteria are used: the output per shift of 7.5 hours, the station utilization, the station constraints, and the relative mean difference of the staff utilization. Zülch and Zülch (2014b) demonstrate for a similar case that a product accompanying staff assignment under production logistical aspects is the best solution, followed by an assignment to adjacent stations. These solutions require four employees (Table 2).

Figure 2. U-shaped assembly system with performance constrained employees.
Due to limited staff skills, it is assumed here that product accompanying staff assignment cannot be realized, which is why the second-best alternative of deploying staff at adjacent stations is used (Solution 1). However, this solution requires that one of the employees operates four stations, while two of them are responsible for three stations, and one of them two stations including the two parallel work places.

Because of the limited skills of staff, this solution is still in doubt, so that only an assignment to a maximum of three stations seems to be feasible (Solution 2). In this case, five employees must be employed.

Finally, it is assumed that two employees have a permanent performance limitation, which leads with each of them to a performance degree (REFA 2011, p. 100) of 75% (Solution 3; see Figure 2). This has an impact on the employees concerned in terms of both, the manual operation times at their assigned stations and the travel times between these stations.

### 3.2 Static planning and evaluation

In terms of production logistics aspects, Solution 1 with four employees, is expected to be the relatively best alternative (Table 3). In terms of ergonomic criteria, however, the metabolic energy expenditure according to Spitzer et al. (1982, p. 151) gives an average value in the range of hard work. The other two Solutions 2 and 3 with five employees are, in contrast, statically seen as moderately heavy.

Table 3. Static and dynamic logistics and ergonomic evaluation of the U-shaped assembly systems (gray/red: best solution; dark/blue: worst solution).

<table>
<thead>
<tr>
<th>Work organization</th>
<th>Number of...</th>
<th>Static evaluation</th>
<th>Ergonomics</th>
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<tr>
<td>...stations...employees</td>
<td>Output per shift</td>
<td>Production logistics</td>
<td>Static evaluation</td>
</tr>
<tr>
<td></td>
<td>Station utilization</td>
<td>Staff utilization</td>
<td>Mean deviat. staff util.</td>
</tr>
<tr>
<td>High staff utilization</td>
<td>4 4</td>
<td>1,000 91% 98% 1%</td>
<td>6,461 6% 14,325 17%</td>
</tr>
<tr>
<td>Station limitation</td>
<td>3 5</td>
<td>1,000 91% 79% 15%</td>
<td>5,069 21% 10,000 27%</td>
</tr>
<tr>
<td>2 employees with performance constraints</td>
<td>3 5</td>
<td>1,000 91% 87% 9%</td>
<td>5,540 17% 9,600 39%</td>
</tr>
</tbody>
</table>

All solutions exhibit high values for the number of necessary steps per employee and shift. In this regard Treut (w/o y) indicates that 10,000 steps a day (and not per shift) should be made (see also NHS 2007). This value is exceeded by almost 50% in Solution 1, and the other solutions correspond in the order of magnitude referred to by these authors. Therefore, Solution 1 is statically seen as overloading the employees.

The static calculations also show that the production outputs for all solutions reach the planned number of 1,000 product units. This is achieved with an equally station utilization of 91%. But, the staff utilization in Solution 1 already suggests with 98% that this form of work organization will lead to a bottleneck, which is why one more employee is then deployed at the other two solutions.
3.3 Dynamic evaluation and assessment

The simulation-aided evaluation demonstrates this accordingly: The output from Solution 1 (Figure 3) with four employees achieves only 664 units per shift, while Solution 2 reaches 738 units with five employees. Solution 3, with two out of five performance constrained staff, is of the same order of magnitude. However, it exhibits a higher utilization of staff including longer operation and travel times due to the performance limitations.

Figure 3. Gantt-chart of a hybrid U-shaped assembly system with staff assignment to adjacent stations.

The ergonomic values are all in the range of moderate work, but Solution 1 has step numbers of about 10,000, which is the recommended amount for a whole day (NSA 2007; Treut w/o y). The other two solutions show lower step numbers but result in higher dispersions of step numbers due to the assumed station limitations resp. performance constraints.

4. Conclusions on the evaluation of U-shaped assembly systems

The case study shows that ergonomic criteria must be considered in addition to the usual production logistics ones, in order to be able to comprehensively evaluate and assess U-shaped assembly systems. However, the question arises whether this case study allows for generalizations.

An important finding in this regard is that static methods are not sufficient for a comprehensive analysis. Instead, the dynamics of the production process must be taken into account by means of simulation. The results show that a static evaluation of U-shaped assembly systems is overly optimistic. In particular, with hybrid model-mix assembly systems, the dynamic process leads to bottlenecks in the interaction of staff and stations that cannot be detected in a static solution. As Zülch and Zülch (2014b, pp. 2186) have shown, a system layout without taking into account staff travel times is insufficient.

With regard to ergonomic evaluation criteria, it should be noted that the calculation of metabolic energy expenditure and steps per shift demonstrated here can be expanded upon. Both criteria are based on the results of each shift output, in this case the number of assembled products. It is important to remember to add criteria concerning the lifting, carrying or pulling of loads. These would then be related to the operations performed by each employee in the simulation, and therefore, for example, in addition to the standard times,
be modelled as other attributes of the manual operation. However, this would amount to an intervention in the FEMOS simulation procedure used here.

Moreover, a variety of questions arise in relation to the inclusion of industrial psychology criteria. Mention should be made here of the frequency of repetition of the performed operations in the simulation, and determination of the share of highly controlled movement elements. Zülch and Braun (1994) offer one feasible approach to this on the basis of the evaluation of the corresponding MTM codes. Furthermore, with respect to production logistics evaluation there are a number of questions. In practice it is well known that, for example, product accompanying staff assignment exhibits benefits, but this is only if operations are uninterrupted. Therefore the question arises, for example, of how production outages can best be absorbed by station buffers.

References


