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PLANNING HYBRID U-SHAPED ASSEMBLY SYSTEMS USING HEURISTICS AND SIMULATION

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ABSTRACT

For small-volume products in particular, U-shaped assembly systems represent an important alternative to straight-line systems. For this kind of system, staff assignment can take various forms: assignment to adjacent and opposing stations, mixed and one-piece flow assignment. In this paper, a U-shaped assembly system is defined on the basis of a known method for balancing straight-line assemblies, and the most suitable form of staff assignment is then determined. If the station layout is interpreted as a capacity graph, and if staff assignment is defined in the form of a staff assignment graph, specific methods must be used to solve the staff assignment problem as those used to match the precedence and capacity graphs for the purpose of line balancing. It is shown that the performance of simulated solutions sometimes varies greatly from that of static balancing solutions, in particular if staff travel times are taken into account.

1 THE GOAL OF THIS PAPER

In this paper we describe a novel planning method for hybrid U-shaped assembly systems with model-mixed order program. Hybrid systems are characterized in that they equally consist of manual and mechanized stations and combinations of them with the consequence that the operation times for man and machine may be different.

The first stage of the planning method is the assignment of assembly operations to stations. For this purpose, known methods can be used, for example mapping the precedence graph of operations on a so-called capacity graph for the assembly stations. The second stage is to adjust this capacity graph to a so-called staff assignment graph in order to define number and qualification of the operators. For this purpose, U-shaped assembly systems demand specific planning methods.

However, the solution obtained in this way is basically a static one because it only insufficiently takes into account existing uncertainties of the ever changing order program and the related operation times. In addition, the travel times of the operators should be considered. Therefore, this static result must be verified by means of a staff-oriented simulation procedure which then takes into account the dynamic effects of these uncertainties and their evaluation can be based on multiple criteria.

2 LITERATURE REVIEW

2.1 Assembly-Planning as an NP-hard Problem

The assignment of operations to the stations of an assembly system is considered an NP-hard problem (Garey and Johnson 1979, Chen and Plebani 2008). This means that the problem can only be solved optimally with a non-polynomial approach. This is why optimal solution methods are normally only available for smaller problem instances.

This statement is particularly true if an assembly system must not only be optimized in terms of machine resources, but also regarding staff resources. Therefore, the operation of several assembly stations by one operator or by a group of operators represents a special problem which can only be solved for practical application cases using heuristic methods so that the required time and effort for its solution are still manageable.

This holds especially true for the definition of machine and staff resources of a hybrid assembly system. Such an assembly system is characterized by machine operation times that may be longer than manual operation times. This is becoming increasingly important as more and more assembly facilities are being automated. It is against this backdrop that the remainder of this paper will assume the operation of semi-automated assembly stations.

2.2 Problem Classes for the Line-Balancing of U-Shaped Assembly Systems

The first paper on a line-balancing problem for U-shaped assembly systems by Miltenburg and Wijngaard (1994) was followed by a whole range of scientific publications that deal with a great variety of problem classes (cf. Boysen, Fliedner, and Scholl 2007 and 2008 for these problem classes). Regarding the work task, one can distinguish between single product systems and model-mix systems from a technical perspective. Another distinction is made based on whether several parallel workplaces can be allocated to the same work station in order to reduce the cycle time. You can also differentiate between systems looking at deterministic or stochastic times for individual assembly operations. The model-mix system includes the additional parameter of whether or not subsequent products of the same type can overtake each other within the system.

The general assumption in literature is to only look at the work stations or the required staff for an assembly system. In this case the model can be referred to as a single-resource model, because either the operation times of the stations (i.e. machining time per unit t_{eB}; symbol as per internationally available terminology according to REFA 2002 which is also used in the following) or the operation times of the operators (activity time per unit t_e) are used as the determinant. If operation times of machines and operators are different, the model is referred to as a two-resource model. This mostly applies to hybrid assembly systems. The inclusion of operator travel times (t_{tr}) into the system model leads to another problem class described by Sirovitnokul and Chutima (2010) in particular.

The case study described below looks at one variant first: a single-resource model is operated with a model-mix and deterministic execution times. The execution time ($t_{d,s}$) at station s is the maximum value derived from the machine or manual operation times of all assembly tasks carried out at this station. Another alternative looks at a system where each individual operator is responsible for several adjacent stations on their own, which makes the system identical to a straight assembly line with possibly shorter return paths. The next variant is a system that allows operators to also work at opposing stations or a mix of adjacent and opposing stations. We will analyze these alternatives both with and without staff travel times.

2.3 Methods for the Line-Balancing of U-shaped Assembly Systems

Contrary to straight-line assembly systems, in a U-shaped assembly system an operation can not only be assigned to a station if all upstream operations have been completed, but also if all upstream or downstream operations have been executed. It is important to note that this only applies to the staff assignment, not to the stations for which we assume being arranged according to their sequence of operations. In addition to the station precedence graph (Prenting and Battaglin 1964) there must also be a phantom graph (introduced by Urban 1998) for the assignment of staff. It takes the form of a preceding mirrored precedence graph.

Just as for straight-line assembly systems, there are two basic possibilities regarding the line balancing approach. One option is to first determine the number of stations and to then define the required cycle time (CT) based on the capacity requirements per product ($C_{BA,i}$) and planning period (or based on the quantity-weighted average of all products i). The other option is to initially divide the duration of the planning period (which equals the available capacity of one station q_{BR} or person q_{MR}) by the quantity of products (m_i) that shall be assembled per planning period. The result is the cycle time with which the number of stations (n_{BA}) can then be determined. The first option forces an integer number of stations, which normally leads to less favourable results than using the second approach. This is why the determination of cycle times is often the preferred approach for real-life applications.

There is a substantial variety of methods discussed in the literature to solve this problem for one of the available problem classes, or a combination of classes. Fattahi et al. (2014, see also Battaïa and Dolgui 2013) present one of the most up-to-date overviews of the methods that are being discussed. Since the problem is an NP-hard one even for the simplest problem classes, mathematical optimization methods can only be used for smaller problem instances. These methods include Integer Programming, Branch and Bound Algorithms and Dynamic Programming as indicated by Miltenburg and Wijngaard (1994). Fattahi et al. (2014) point out that it is very difficult to apply these methods to real-world problems, e.g. model-mix problems that at the same time are also multi-objective problems and have stochastic operation times. Kara and Tekin (2009), for example, have developed a Mixed Integer Linear Program for U-shaped model-mix lines with a fixed order sequence.

It is for this reason that heuristic or meta-heuristic methods are suggested for the solution of practical problems. Even though they do not guarantee a strictly mathematical optimization, they promise to yield good solutions. The heuristic solution methods for U-shaped assembly systems include the Phantom Network Method as described by Urban (1998). Recently, more and more meta-heuristic methods have been used, e.g. Simulated Annealing, Genetic Algorithms and Colony Optimization. These approaches have been used in specific application cases for stochastic operation times and for the inclusion of staff travel times.

These methods, however, have a disadvantage as dynamic effects from the production process cannot be factored in appropriately, e.g. due to varying order programs. Therefore, their results must be considered as static solutions with the assumption of specific restrictions. Also, the interaction between operators and stations one would have in hybrid assembly systems cannot be included in such a method, which is another substantial deficiency. In this case, machining times per station exceed operator activity times, which is the basic prerequisite for multi-machine operation to be possible in the first place.

2.4 Simulation of U-shaped Assembly Systems

Given the above facts, it is even more surprising to see that there are only relatively few authors who cover the use of simulation for designing U-shaped assembly lines. After all, machine and staff resources can be modelled separately using appropriate simulation procedures, and their interaction can be simulated realistically. If required, order sequences in model-mix systems, stochastic operation times and operator travel times can be factored in and revised for their sensitivity.

Wang et al. (2009) use a combination of mathematical modelling and simulation in order to analyse a linear walking worker assembly line, i.e. a one-piece flow system. Tiacci (2012) describes a *JAVA*-based simulation for model-mix assembly lines including stochastic operation times, parallel stations, a fixed scheduling sequence and buffers between work stations. His simulation procedure is suitable for modelling both straight-line and U-shaped systems. Martinez and Bedia (2002) present a modular program based on the *WITNESS* simulation procedure, which is used to model a U-shaped assembly system. Baykoç (2008) uses an adapted heuristic method, which had originally been developed by Arcus (1966) under the name of *COMSOAL* (*Co*mputer *M*ethod of *S*equencing *O*perations for *A*ssembly *L*ines). They use the approach to model a U-shaped single-product assembly system for washing machines and analyse its behaviour employing the *ARENA* simulation procedure. Finally, Eryürük (2012) works with different heuristic methods to re-balance a clothes production line. Afterwards, she simulated the systems using the *ARENA* procedure. As a result, a U-shaped assembly system turns out to be advantageous over a straight-line system. It must be noted that this conclusion does not necessarily apply to all types of U-shaped systems.

3 A COMBINATION OF STATIC AND DYNAMIC PLANNING

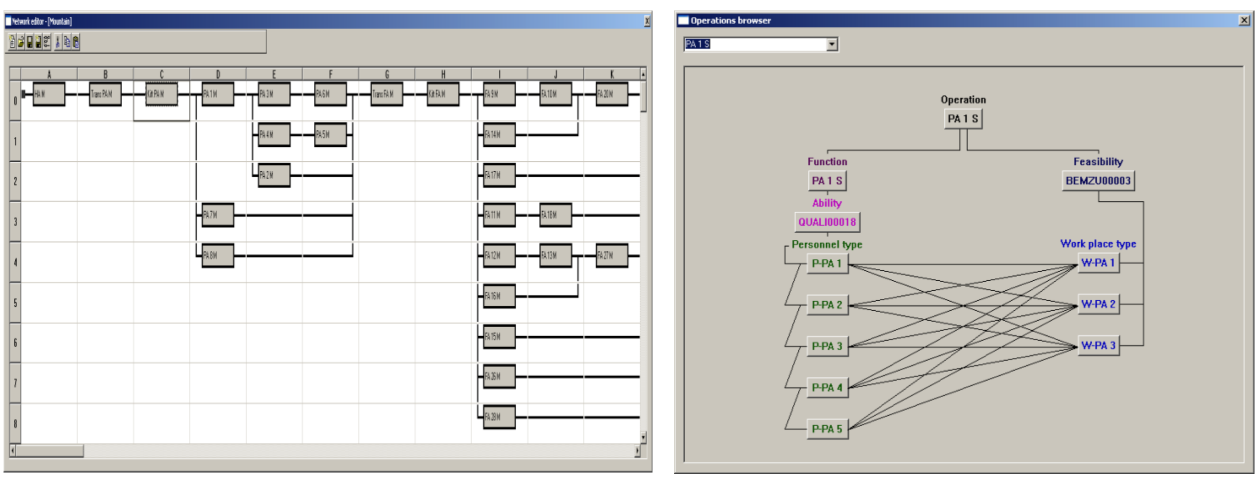
3.1 Advantages of Method Combination

The general conclusion is that the majority of existing publications do look into static planning with different optimization methods, heuristic methods and meta-heuristic methods. However, only few authors work with simulation to analyze the dynamic effects of a U-shaped assembly line. Mostly, a static solution is chosen as a basis for subsequent simulation, which is then used to improve the initial solution under stochastic influences, if necessary.

However, it must be noted that for both static planning and simulation it is necessary to choose between the stations or the operators as a frame of reference. To the knowledge of the authors of this paper, hybrid systems with their mix of manual, mechanized and automated operations are not discussed in the literature. In order to model hybrid model-mix assembly systems, what is referred to as a staff-oriented simulator is required. Such a simulator allows for the inclusion of both resources as separate elements into the simulation model.

3.2 Description of the *FEMOS* Simulator

The *FEMOS* simulation procedure (German acronym for "Parts Production and Assembly Simulator") is used for the example described below. *FEMOS* is a simulator that has been developed by the *ifab*-Institute of Human and Industrial Engineering of the Karlsruhe Institute of Technology since 1988. This paper includes only a brief outline of the procedure, as more detailed descriptions of the concept and relevant case studies are available in the literature (e.g. Zülch and Grobel 1996, Zülch, Rinn, and Strate 2001, Zülch and Brinkmeier 2003, Zülch, Waldherr, and Zülch 2010).



Modelling of an activity netgraph of an order type with its operations

Relations between function, personnel type and workplace type

Figure 1: Basic modeling concepts of the simulation procedure *FEMOS*.
(The labels in the nodes are used for identification.)

FEMOS has been developed with a focus on the interaction of staff and machine resources and can therefore be considered a staff-oriented simulation procedure as defined in the relevant guideline of the Association of German Engineers (VDI 3633-6, 2001). The product types to be manufactured are modeled in the form of activity netgraphs (Figure 1, left). They can be initiated several times within the simulation period and represent the production program for the period under review. The operations are modelled as activities on nodes which can be described by attributes. These attributes include the person or group of persons required to do the operation as well as the machine, group of machines or work stations. Both types of resources are modelled separately, which allows for different operation times for persons and machines, different activity times for different persons and differing machining times to be included.

This way, a group of operators, a group of machines and a group of work stations can be assigned to a function. A function will group identical operations from different activity netgraphs. It has proved helpful to review the resulting relations in a separate browser to verify the model's consistency. In this browser, all relations between the individual elements of the model must form solid lines (Figure 1, right).

The simulator is used to verify an existing solution produced by static planning dynamically in terms of the fixed order sequence which may then be improved through a trial and error approach. Compliance with different objectives can be evaluated, including production- and logistics-related goals as well as staff- and cost-oriented goals which are implemented in *FEMOS*. The evaluation can be based on standardized goal achievement levels ranging from 0% and 100% with the two extreme values often being impossible to be reached in real-life applications. Regarding a specific goal, the lower limit will be reached with a pessimal solution, whereas the upper limit will be achieved with an optimal solution. It is up to the user to decide whether several objectives are supposed to be combined into a global value, e.g. using an additive, lexicographical or pareto-optimal (functional-efficient) preference function.

3.3 Planning Steps to Determine an Initial Static Solution

As indicated by the above-described method combination, the simulation is based on an existing initial solution. Here, the assembly precedence graph is taken as the starting basis. Using one of the above-mentioned methods, the stations of the assembly system must be mapped on this precedence graph. Dittmayer (1980) shows that different forms of work division can be modelled, i.e. assembly lines, a system composed of individual working groups or a system consisting of as many individual work places as required for the task (see also Warnecke and Dittmayer 1981).

Braun (1995) interprets these layouts as capacity graphs and develops the first rules for the best possible mapping of a capacity graph on the precedence graph. It can be seen from a publication by Müller (2002) that a staff assignment graph must be mapped on this capacity graph in order to model the assignment of staff within the assembly system (for a more detailed description of this approach, cf. Zülch and Zülch 2014).

Currently, no generally applicable approach has yet been published as to how a staff assignment graph could be mapped on an existing capacity graph in a U-shaped assembly system. Zülch, Leupold, and Gamber (2012) just present the concept of a backtracking algorithm with partial enumeration and simulation to solve this problem for a single-product assembly system with a given goal function.

4 CASE STUDY OF A HYBRID U-SHAPED MODEL-MIX ASSEMBLY SYSTEM

4.1 Characterisation of the Problem

Below, the combination of planning method and simulation is described based on a case study. It is assumed that a capacity graph has already been mapped on a precedence graph using. Based on this initial solution, a staff assignment graph is mapped on the capacity graph for U-shaped assembly systems. The resulting static solution may later be improved by carrying out simulations of staff assignment alternatives. The individual work of operators is taken into consideration in the form their assignment to adjacent or opposing stations, a mix of both of these and a one-piece flow system. Furthermore, these systems are considered with and without the inclusion of travel times.

The case study regards an hybrid assembly system based on Müller (2002), which in turn is a modification an older one-of-a-kind example by Buxey (1974), which again has its origin in a publication by Arcus (1966). For the purpose of staff assignment, the time unit mentioned by Müller (2002) is taken to be seconds. The solution presented here has a cycle time of 26 seconds and 12 stations, of which one is a parallel station with two work places.

The problem has been extended to include the option of a model-mix assembly system. The same volume of 1,000 units per day then includes four different types of products that partly require differing station times (Table 1). The order program is generated stochastically with a minimal batch size of 1 unit, and orders for the same type of product are bundled. This leads to order batch sizes of 1 to 8 units. A hybrid assembly system is modelled by reducing manual operation times to approximately one fourth of station times (Table 2).

Table 1: Assembly program and station data of the modified Buxey problem.

Buxey problem,	**modified**	**machinery**														
Model assumptions																
ES [h/shift*ma]			qBR [sec/d*ma]		CT [sec]	CT [min]		QBE=QBA [sec/d]								
7.2			25,920		26	0.4320		CBE=CBA [sec/d]								
					25.92											
Assembly program	**original**	s	1	2	3	4	5	6	7	8	9	10	11	12	nBA	13
		j	1, 2	6, 7, 9, 10	3, 4, 14, 25	5, 24	8, 12	13, 16, 26	11, 15	17, 18, 20	19, 21	22	23, 27	28	QBA [sec/d]	336,960
	i	m [1/d]														
teB,s [sec]	1	1,000	26	26	22	26	26	26	52	25	25	25	21	20	teB [sec]	320
CBA,s [sec/d]	1		26,000	26,000	22,000	26,000	26,000	26,000	52,000	25,000	25,000	25,000	21,000	20,000	CBA [sec/d]	320,000
															Station utilization	0.950
Assembly program	**model-mix**	s	1	2	3	4	5	6	7	8	9	10	11	12		
		j	1, 2	6, 7, 9, 10	3, 4, 14, 25	5, 24	8, 12	13, 16, 26	11, 15	17, 18, 20	19, 21	22	23, 27	28		
	i	mi [1/d]													teB,i [sec]	CMB,i [sec/d]
teB,is [sec]	1	500	26	26	26	26	26	26	52	25	25	25	21	20	324	162,000
modified	2	300	26	26	24	25	24	23	52	25	24	24	21	20	314	94,200
	3	150	26	24	26	26	23	23	50	28	24	24	24	24	322	48,300
	4	50	21	22	25	24	24	24	50	24	24	24	24	24	310	15,500
teB,s [sec]		1,000	25.75	25.50	25.35	25.60	24.85	24.55	51.60	25.40	24.50	24.50	21.60	20.80	CBA [sec/d]	320,000
															Station utilization	0.950
CBA,is [sec/d]	1		13,000	13,000	13,000	13,000	13,000	13,000	26,000	12,500	12,500	12,500	10,500	10,000		
	2		7,800	7,800	7,200	7,500	7,200	6,900	15,600	7,500	7,200	7,200	6,300	6,000		
	3		3,900	3,600	3,900	3,900	3,450	3,450	7,500	4,200	3,600	3,600	3,600	3,600		
	4		1,050	1,100	1,250	1,200	1,200	1,200	2,500	1,200	1,200	1,200	1,200	1,200		
CBA,s [sec/d]	Sum		25,750	25,500	25,350	25,600	24,850	24,550	51,600	25,400	24,500	24,500	21,600	20,800		
Technical station structure																
nBA,is [1]	1		0.502	0.502	0.502	0.502	0.502	0.502	1.003	0.482	0.482	0.482	0.405	0.386		
	2		0.301	0.301	0.278	0.289	0.278	0.266	0.602	0.289	0.278	0.278	0.243	0.231		
	3		0.150	0.139	0.150	0.150	0.133	0.133	0.289	0.162	0.139	0.139	0.139	0.139		
	4		0.041	0.042	0.048	0.046	0.046	0.046	0.096	0.046	0.046	0.046	0.046	0.046		
nBA,s [1]	Sum		0.993	0.984	0.978	0.988	0.959	0.947	1.991	0.980	0.945	0.945	0.833	0.802	nBA [1]	12.346
nBA,s [1], rounded up			1	1	1	1	1	1	2	1	1	1	1	1	nBA [1], round.up	13
															CBA [sec/d]	320,000
															Station utilization	0.950

4.2 Description of the Static Solution Method

In the first stage the precedence graph of the operations must be mapped on the capacity graph. This can basically be done with the same optimization and heuristic methods known from balancing of straight-line assembly systems. The Ranked Positional Weight Method by Jackson (1956) can be used for heuristic optimization. This method presents the advantage of being relatively easy to apply and being usable in practice without requiring expertise in special operations research methods.

For assigning operators to the assembly stations the problem is reduced in complexity as the capacity graph of a hybrid assembly system normally has fewer nodes than the precedence graph. For this second stage we propose the Phantom Network Method by Urban (1998). which is a modification of the original method in such a way that the capacity graph is subdivided to cover the two opposing legs of the line (Figure 2). The ranked positional weight (RPW_s) of an assembly station s is the operation time of that station plus the operation time of all subsequent stations. In this case, the ranked positional weight is calculated starting from the beginning of the assembly system up to the middle, and then starting from the end of the assembly system again up to the middle. If the number of stations is uneven, the mean of the two ranked positional weights is assigned to the middle station (cf. bold italics number in Figure 2). This way, the Modified Ranked Positional Weight Method forces one operator to be mainly assigned to opposing stations.

Table 2: Staff assignment to opposing stations of the modified Buxey problem

Buxey problem,	**modified,**	**staff**														
Model assumptions																
ES [h/shift*pe]			qMR [sec/d*pe]		CT [sec]	CT [min]		CME=CMA=CBE [sec/d]								
7.2			25,920		26	0.4320		QME=QMA=QBE [sec/d]								
Staff assignment	**s**		1	2	3	4	5	6	7	8	9	10	11	12	nBA	13
	j		1, 2	6, 7, 9, 10	3, 4, 14, 25	5, 24	8, 12	13, 16, 26	11, 15	17, 18, 20	19, 21	22	23, 27	28		
	i	mi [1/d]													te,i [sec]	CMA,i [sec/d]
te,is [sec]	1	500	7	7	7	7	7	7	13	7	7	7	6	5	87	43,500
25% of teB,is	2	300	7	7	6	7	6	6	13	7	6	6	6	5	82	24,600
rounded up	3	150	7	6	7	7	6	6	13	7	6	6	6	6	83	12,450
	4	50	6	6	7	6	6	6	13	6	6	6	6	6	80	4,000
m [1/mon]	(weighted) Sum	1,000	6.95	6.80	6.70	6.95	6.50	6.50	13.00	6.95	6.50	6.50	6.00	5.20	CMA [sec/d]	84,550
															nMA [1], round.up	4
															Staff utilization	0.815
CMA,is [sec/d]	1		3,500	3,500	3,500	3,500	3,500	3,500	6,500	3,500	3,500	3,500	3,000	2,500		
	2		2,100	2,100	1,800	2,100	1,800	1,800	3,900	2,100	1,800	1,800	1,800	1,500		
	3		1,050	900	1,050	1,050	900	900	1,950	1,050	900	900	900	900		
	4		300	300	350	300	300	300	650	300	300	300	300	300		
CMA,s [sec/d]	Sum		6,950	6,800	6,700	6,950	6,500	6,500	13,000	6,950	6,500	6,500	6,000	5,200		
Operation of opposing stations																
nMA,is [1]	1		0.135	0.135	0.135	0.135	0.135	0.135	0.251	0.135	0.135	0.135	0.116	0.096		
	2		0.081	0.081	0.069	0.081	0.069	0.069	0.150	0.081	0.069	0.069	0.069	0.058		
	3		0.041	0.035	0.041	0.041	0.035	0.035	0.075	0.041	0.035	0.035	0.035	0.035		
	4		0.012	0.012	0.014	0.012	0.012	0.012	0.025	0.012	0.012	0.012	0.012	0.012		
nMA,s [1]						0.777			0.752		0.770			0.963	nMA [1]	3.262
nMA,s [1], rounded up						1			1		1			1	nMA [1], round.up	4
															QMA [sec/d]	103,680
															Staff utilization	0.815
te,s [sec]	(weighted) Sum		6.95	6.80	6.70	6.95	6.50	6.50	6.50	6.50	6.95	6.50	6.50	6.00	5.20	
RPWs	folded		84.55	77.60	70.80	64.10	57.15	50.65	44.15	53.40	60.35	66.85	73.35	79.35	84.55	
									46.90							
									45.53							
te,p [sec]										19.50	20.40		19.70		24.95	
RPWp										149.58	184.35		211.00		326.05	
										1	1		1		1	

This method is sufficient for static solution finding and even provides several heuristically optimal solutions. In our example, four operators (p) are needed for the assembly system (n_{BA} in Table 2). The application of the method shows that the assignment of staff to adjacent stations (like in a straight-line assembly system) requires four operators with an average operator utilization rate of 81.5% and a station utilization rate of 95.0% (Table 3).

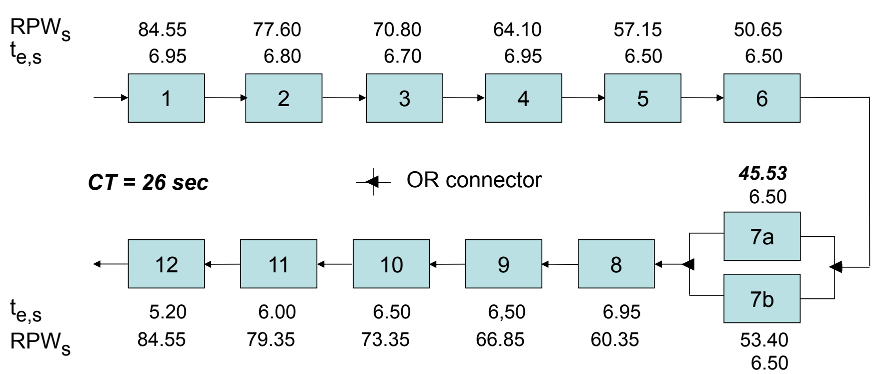


Figure 2: Capacity graph, activity times and ranked positional weights of the modified Buxey problem.

The individual operator utilization rate, however, varies between 77.0% and 96.3% (Table 2). The latter value already indicates that a dynamic analysis is likely to highlight a bottleneck. Solutions where the staff is assigned to opposing or mixed stations reveal a slightly worse range of staff utilization (Table 3). Only the one-piece flow system shows an equal distribution of utilization among the operators.

Table 3: Comparison of results with and without travel times.

Solution	Static calculation				Simulation without travel times				Simulation with travel times			
	Output per day	Station utilization	Staff utilization	Range of staff utilization	Output per day	Station utilization	Staff utilization	Range of staff utilization	Output per day	Station utilization	Staff utilization	Range of staff utilization
No staff restrictions	1000	95.0%	-	-	992	95.0%	-	-	-	-	-	-
Staff assignment to adjacent stations	1000	95.0%	81.5%	16.4%	790	75.0%	64.4%	12.9%	680	64.4%	82.2%	29.4%
Staff assignment to opposing stations	1000	95.0%	81.5%	19.3%	689	65.5%	56.3%	14.4%	641	60.8%	78.8%	31.0%
Mixed staff assignment	1000	95.0%	81.5%	19.3%	689	65.5%	56.3%	14.5%	639	60.7%	77.4%	30.7%
One-piece flow	1000	95.0%	81.5%	0.0%	995	94.5%	81.2%	18.0%	823	78.1%	96.4%	3.0%

However, a heuristically optimal staff assignment is not necessarily mathematically optimal or unique as in our example. The static solution for assignment of staff to opposing station results in a staff assignment graph shown in Figure 3 with rounded nodes. One of the four operators takes care of the four opposing stations at the beginning and at the end of the assembly system, the second operator covers the three stations located at the narrow end, and the remaining two operators handle three opposing stations each. The average utilization rates for stations and operators remain the same, but individual staff utilization rates now range from 75% to 96%. The same values are generated if operators 2 and 3 are assigned to adjacent stations, which means that statically several heuristically optimal solutions are feasible.

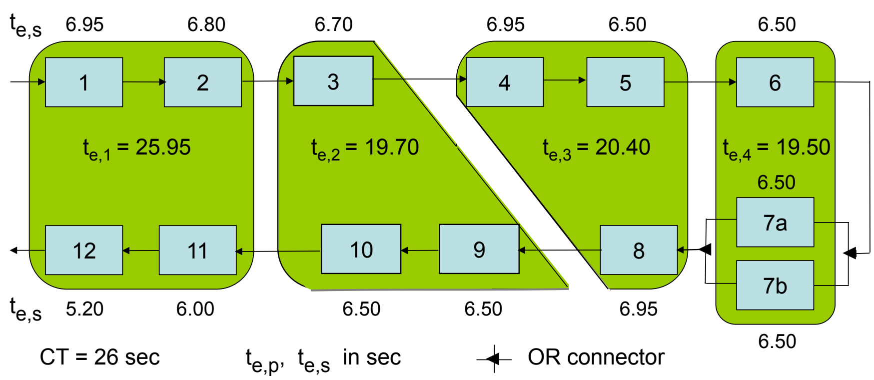


Figure 3: Staff assignment graph and activity times per person.

4.3 Dynamic Verification of Staff Assignment using Simulation

The resulting solution alternatives are then analysed for their dynamic behaviour using the simulation procedure *FEMOS* (Section 3.2). In the case of no staff restrictions, the simulator produces nearly the same results as for the static solution (Table 3).

Regarding the staff assignment to adjacent, opposing and mixed stations, the statically planned production rate of 1,000 assembled products per day cannot be achieved by far (Table 3). The station utilization is down by approximately 20% for the staff assignment to adjacent stations, and even 30% if the staff is assigned to opposing, while the range of staff utilization shows some better results compared to the static solutions, thus indicating a slight improvement of equal job distribution. The one-piece flow gives the best results concerning station and staff utilization. But the range of the latter is higher than in the former solutions, which shows more inequality of job distribution.

It is known that travel times can have a significant impact on the productivity of U-shaped assembly systems, if they are similar to the manual activity times per station or the cycle times. Travel times for the U-shaped assembly system were determined by means of the MTM-1 method. In addition to straight-line walking (MTM code LM-[cm]), all required rotational movements of the body (MTM codes TBC1 and TBC2) were taken into consideration as well (Figure 4). The travel times, which range from 3.1 to 6.4 seconds, are similar to the station activity times ranging from 5.2 to almost 7.0 seconds.

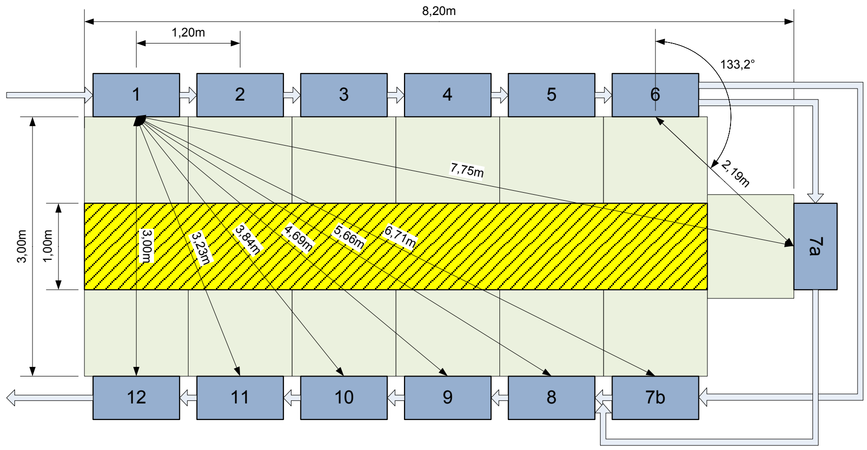


Figure 4. Layout of the U-shaped hybrid assembly system.

Therefore, the situation becomes even worse if travel times are included. The output rate drops down to 68% for staff assignment to adjacent station, and to 61% in the case of opposing and mixed assignment (Table 3). Staff utilization increases and achieves about the same level as in the static case. But the range of it reaches about the double values compared to those of the simulation without travel times, illustrating a rather uneven distribution of jobs among the operators.

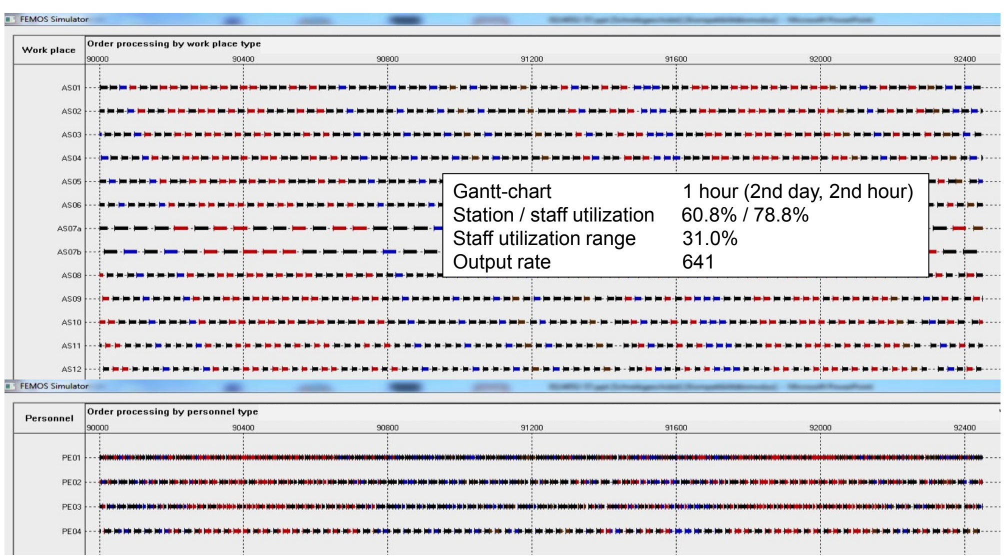


Figure 5: Order processing with travel times and staff assignment to opposing stations.

This procedure is illustrated by a modified example from literature. Based on an existing solution for the capacity graph showing the assignment of assembly operations to stations, the Modified Ranked Positional Weight Method is used to derive the staff assignment graph. The simulation of various forms of staff assignment to stations shows that in the present case study the one-piece flow is the most appropriate solution even when travel times are taking into account.

This result is illustrated by the Gantt chart of order processing in Figure 5 in case of staff assignment to opposing stations. The bars show the utilization of work stations (AS) and that of the personnel (PE) over a certain time scale of the simulation run, which is measured here in seconds. Their lengths are depicting the duration of operations and travels, the various colours illustrate individual orders. The order processing with travel times shows some idle times at the work stations. The staff has much less waiting times, but the range of utilization is with nearly 31% much less balanced than in the other solutions.

The one-piece flow system achieves the best results: Nearly all the demanded quantity can be assembled without travel times but only 82% of it when travel times are included (Table 3). Station utilization is about 78% with travel times, but staff utilization reaches more than 96%. With 3% range of staff utilization the jobs can be regarded as evenly distributed, but the staff is on the edge of being overloaded. A specific requirement of this solution is certainly that the operators must be fully qualified for all jobs.

5 CONCLUSIONS AND OUTLOOK

Our paper proposes a two-stage method for planning hybrid U-shaped assembly systems with model-mix order program. For the first stage, which is the assignment of assembly operations to stations, known methods for line balancing can be used. The second stage required for the assignment of operators to the U-shaped layout of stations requires special methods. However, the result obtained is basically static, since it only inadequately takes into account uncertainties in the composition of the order program and in the related operation times. Therefore, the result must be verified dynamically by simulation. In this way, assessment can be based on multiple criteria.

In further studies the relation of travel time to cycle time or operation time per station that will cause a substantial influence on the overall result must be investigated in more detail. Furthermore, buffer dimensions should be determined statically for model-mix systems as a first step. Following this, they can then be modified using simulation.

U-shaped model-mix assembly systems have proven their value in the field on many occasions. Still, there is a range of open questions left for further research activities, in particular if station zone restrictions and staff qualification restrictions are to be considered.

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