CHAPTER 10

CONCURRENT APPROACH TO DESIGN ASSEMBLY LINE

Weeks later when the visitor asked him
what he taught his disciples, he said,
'To get their priorities right: better
have the money than calculate it; better
have the experience than define it.'

Anthony de Mello, One Minute Wisdom

Keywords: assembly line design, concurrent design, logical line layout, interactive and iterative design.

1. Introduction

Designing an assembly system is a hard mission that necessitates many complex decisions. Numerous choices must be made at each design step which affect the time and cost to assemble the products. As shown in Chapter 1, ALD involves the design of products, processes and plant layout before the construction of the line itself. These different modules interact at the different stages of the ALD. The product analysis (PA) proposes a first product design review, based on DFA rules and precedence constraints between assembly tasks. The operating modes and techniques (OMT) module proposes an assembly technique and the possible modes (manual, automated, robotic) for each task. The LL module assigns tasks to stations, and decides about the position of stations and resources on the plant floor.

This chapter is organised as follows: in section 2, a brief description of ALD problem is given, discussing its constraints as well as its objectives. The first phase of the integrated approach which is the "preparation of data" is introduced in section 3.

Section 4 is devoted to the optimisation phase while the mapping phase is described in section 5. Results of two industrial case studies are presented in section 6, and conclusions are drawn in section 7.

2. Concurrent approach

As shown above the integrated method is composed of three independent modules namely the PA, the OMT and the LL. It is always possible to use only one of them, its input being given by the designer. The product design and ALD do not start from scratch. Designers have always an idea on how to design the product (tacking into account the plant constraints). At the same time the proposed line designs are most of the time influenced by the way the product will be assembled (PA and OMT outputs). In fact, there is a *simultaneous* design of the product and its line such that fixing the product structure limits the possibilities of the line architecture.

The PA module proposes a first decomposition of the product into subassemblies and a set of geometrical precedence constraints between components. These data are analysed and completed to yield a precedence graph. At this stage the assembly technique is not yet taken into account. The OMT determines the possible techniques and modes and completes the description of the assembly operations with feeding and manipulation operations. The output is a list of feeding, handling and assembly operations with one or more associate mode preferences, a time and a cost for each mode, and precedence graph between operations. Finally, each precedence graph will be completed by the user with miscellaneous operations, (e.g, control), yielding a complete graph that will be the input data of the line layout module.

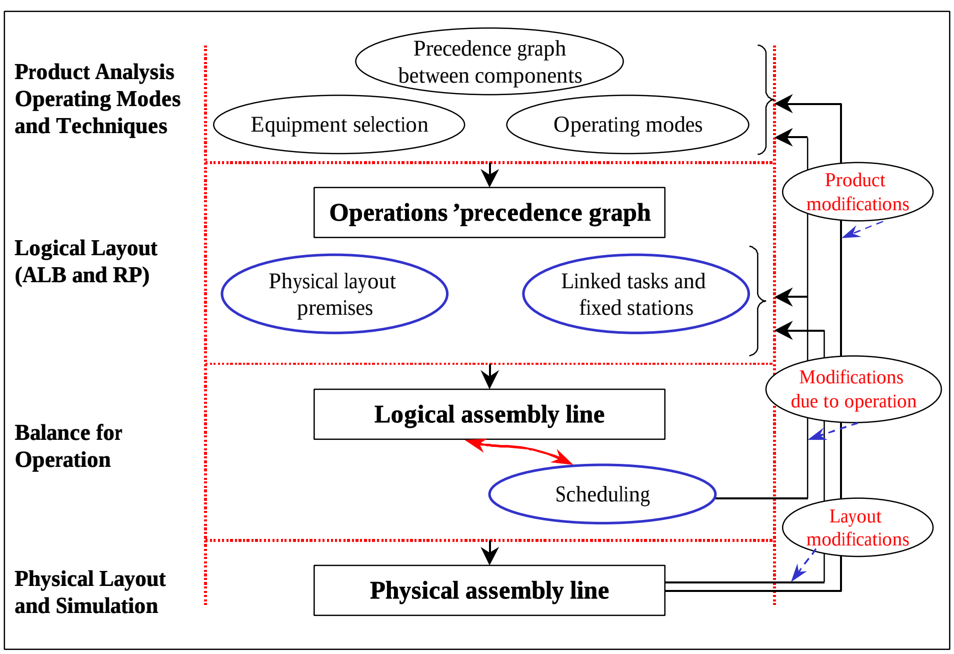

Figure 10.1. Concurrent design of assembly line.

The principal features of the line layout module were introduced in the former Chapters. That is, the logical layout (ALB and RP) were presented respectively in chapters 6 and 7. The balance for operation concept is presented in chapter 8.

Thus, the integrated ALD approach is illustrated in the following pseudo-code:

repeat
Fix on the operating modes and techniques of tasks;
Select equipments for each task;
Cluster tasks between workcenters;
Impose grouped tasks and fixed stations to recover existing stations;
Balance for operation the line;
    repeat
        Propose the logical layout of the assembly line;
        Test the operating efficiency of the assembly line;
    until *satisfactory solution has been found;*
    Decide about the disposition of the stations, conveyors, buffers, on the shop floor;
    Simulate the assembly line to investigate the impact of obtained architecture;
until *a satisfactory assembly line architecture has been found;*

In summary, the ALD can be seen as the execution of the following steps: (1) fix on the assembly type, (2) draw the precedence graph, (3) describe the whole process, (4) decide about the line speed, the cycle time and number of stations, (5) use the integrated approach, and finally (6) evaluate the efficiency of the obtained line (see Figure 10.1).

If the proposed design is not satisfactory, the operating modes or precedence graph, etc. will be modified. Product modifications can also be envisaged at this late stage but only if other modifications are ineffective. A feedback to previous steps of the process is always possible.

In the next section a framework of the proposed assembly line layout is presented.

3. Assembly line design

The proposed method is built upon many collaborations with industrials. Its main steps can be summarised as follows (see Figure 10.2):

- **Preparation** The designer introduces its input data (tasks, resources, constraints, preferences, etc.);
- **Optimisation** The optimisation method proposes a line architecture (stations contents, their order, etc.);
- **Mapping** Allows the designer to analyse and test the results using a simulation package.

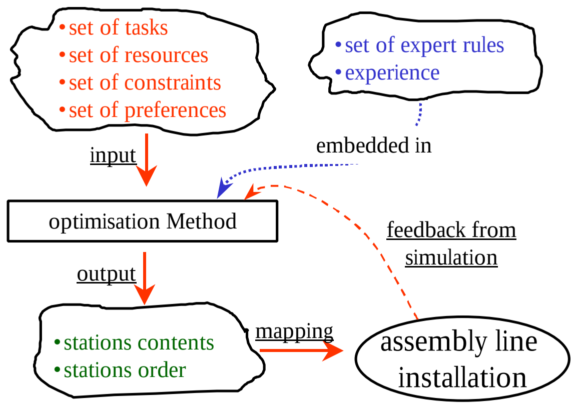

Figure 10.2. Design method.

3.1. Data preparation phase

Once the product and the existing resources of the enterprise has been analysed a set of assembly plans are proposed as well as their preferable resources. For more details about this phase the reader is suggested to refer to (Pellichero, 1999). The method yields the following input for the optimisation phase, as illustrated on Figure 10.3:

- the desired number of stations,
- the desired cycle time.
- for each task:
- the precedence constraints between this task and the other ones,
- the user's mode preferences (manual, automated or robotic).

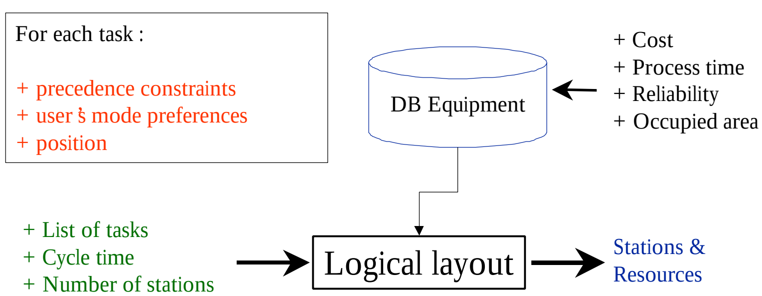

Figure 10.3. Data flow of the ALD method.

3.2. Optimisation phase

This phase constitutes the evolutionary computation part of the methodology. The approach is based on GAs and many industrial designers' ideas, which are embedded in the method as heuristics. In sections 4 and 5, we will illustrate the use of the two proposed tools to the ALD namely the EPLB and the RP presented respectively in chapters 6 and 7. Two industrial case studies will be presented. The main aim is to describe how they can be effectively used in a concurrent design approach.

3.3. Mapping phase

The optimisation module yields a logical-layout of the line. A solution contains the following information:

- cycle time,
- number of stations,
- for each station:
- process time,
- a list of tasks, their mode, order as well as their position,
- a list of resources.

This information only constitutes the logical-layout of the assembly line presented on the left side of Figure 10.4. The right part shows a real installation of an assembly line and its relative representation which comes from the optimisation module.

The missing step of the physical layout is replaced by an interactive method. Each station is represented by an object (square) and is defined by a list of tasks, a list of resources, its order among the other stations, etc. The mapping phase helps the designer to make a first draw of the assembly line.

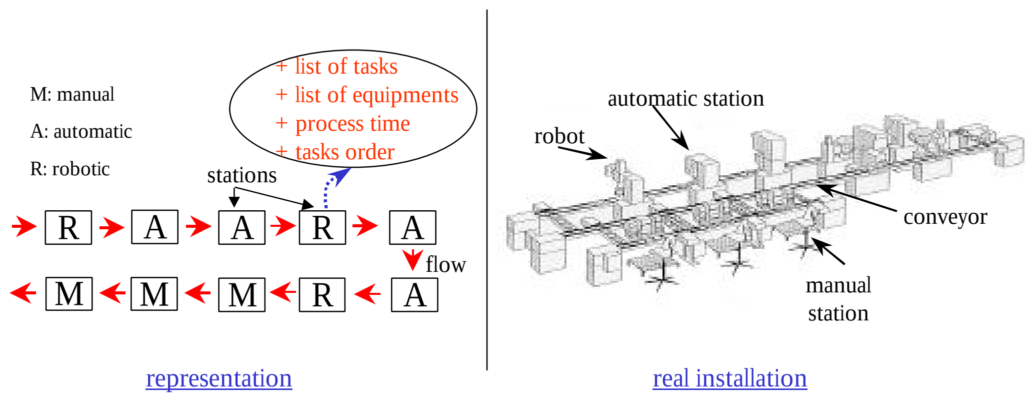

Figure 10.4. Relationship between the real architecture of the line and its representation.

The optimisation module have to save the obtained assembly line architecture in a specified format, which are then used by the simulation module (AUTOMOD) software package (Wanet, 1999). The AUTOMOD input data needed to design the system are:

- locations: it correspond to real location of stations,
- entities: pallets, parts, all items which are moving between different locations,
- resources: describe operators, conveyors, machines which are able to move entities between two locations, or can execute an operation.
- tasks: description of tasks as well their order on each station.
- path network: paths imposed to resources and/or entities in the real system,
- processing: allows to define possible destinations of an entity leaving a location. The station's duration spent on each product, is deduced using a matrix of processing times,

Figure 10.5 shows the *virtual* representation of an assembly line as it done in AUTOMOD software (Wanet, 1999). It represents four stations connected by a conveyor. Tasks are accomplished by one operator, two dedicated machines and one robot.

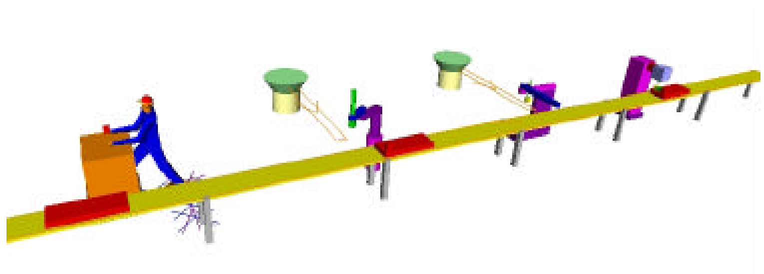

Figure 10.5. An AUTOMOD representation of an assembly line.

4. Case studies

The next section present of our two main approaches (EPAL and RP) on two industrial case studies

4.1. ALB application : Outboard motor

The studied product is a 'outboard motor marine' engine. The aim is to balance the workload for a fixed number of stations. The line produces between *9* and *11* engines per hour, according to the period of year. Table 10.1 summarises the tasks performed on the product. It shows the workcenter, the process time (tenth of an hour) and the precedence constraints for each task. There are *155* operations. The tasks whose number_id is less than *450* belong to the first workcenter (the remaining ones belong to the second workcenter).

The plant in this case is composed of two workcenters. The aim consists in balancing the workload of the assembly line using different number of stations. The first configuration supposes that there is no link between workcenters, while in the second one workcenters are linked by their last stations. The two workcenters are linked by an ‘operations exchange’ link (for more details see Chapter 9 section 4.2.2.4).

Op	WkC	Duration	Preds	Op	WkC	Duration	Preds	Op	WkC	Duration	Preds	Op	WkC	Duration	Preds
12	0	0.1		**132**	0	4	130	**302**	0	3.7		**455**	1	3.4	
15	0	0.5		**135**	0	1.2		**305**	0	4		**457**	1	5.5	455
17	0	1		**137**	0	3.5	135	**307**	0	3.1		**460**	1	2.5	455
20	0	0.5		**140**	0	5.5	137	**310**	0	1.2		**462**	1	4.5	457, 460
22	0	0.7		**147**	0	5.5		**312**	0	3.6	225	**465**	1	10	462
25	0	0.3	22	**152**	0	3.3	147	**317**	0	2.2		**467**	1	4.5	
27	0	3		**155**	0	3.3	152	**320**	0	1.5		**470**	1	7	
30	0	3.6	27	**157**	0	3.3	155	**322**	0	3.2		**475**	1	4.5	
32	0	3.6		**160**	0	2.2		**325**	0	1.3		**477**	1	5	
35	0	0.3		**162**	0	2		**327**	0	1.3		**480**	1	3.4	
37	0	3.5		**165**	0	1.5	162	**330**	0	1.2		**482**	1	8	
40	0	3.5		**167**	0	3.3		**332**	0	1.2		**485**	1	4.5	
42	0	5.1	40, 35	**170**	0	1		**335**	0	5		**487**	1	2	
45	0	5.1		**172**	0	5.5	170	**337**	0	1		**490**	1	3.3	
47	0	5		**180**	0	3.3		**338**	0	1.7		**507**	1	1	
50	0	5	40	**182**	0	4.2	180	**339**	0	4.4	185	**512**	1	5	
52	0	0.8		**185**	0	4.4	182	**347**	0	3.6	185	**515**	1	4.8	
55	0	0.6		**190**	0	1.8		**350**	0	1.7		**516**	1	1.2	
60	0	2.8		**193**	0	2.5	185	**355**	0	4.8	240	**517**	1	3.3	
62	0	0.9		**197**	0	1.6	185	**357**	0	1.1	310	**520**	1	8.5	
65	0	1.3	60	**225**	0	2.4	190, 193, 197	**367**	0	0.6		**522**	1	5	
67	0	2.5	62, 65	**227**	0	9.5		**372**	0	3.8	355	**525**	1	4	
70	0	4.6	62, 65	**237**	0	7.2		**380**	0	6	355	**527**	1	5	
75	0	10	62, 65, 70	**240**	0	1.5		**387**	0	0.6		**530**	1	6.6	
87	0	1.8	75	**241**	0	2.2	240	**395**	0	1.7	357, 339, 312, 350, 265,	**532**	1	5.5	
90	0	3.3		**243**	0	3.3					292, 237, 243, 247, 372, 380,	**535**	1	6	
97	0	1.7		**245**	0	5.7	240				252, 367, 280, 387, 282, 338	**537**	1	8.5	
100	0	0.7		**247**	0	1.2		**397**	0	2.2	185	**540**	1	4.4	
102	0	5.5		**252**	0	0.4		**400**	0	6	395, 397, 67	**542**	1	2.5	540
106	0	2.4		**257**	0	5	185	**402**	0	1	400	**545**	1	5	
110	0	4.2	106, 122	**265**	0	0.6		**405**	0	3.6	402	**547**	1	3.4	
112	0	2.4	110	**280**	0	2.4		**410**	0	4.2		**550**	1	4.2	547
115	0	2.6		**282**	0	3.3		**415**	0	3	410	**552**	1	7.5	550
117	0	4		**285**	0	6	185	**417**	0	4.4		**555**	1	13.5	
120	0	1.1		**287**	0	4		**420**	0	4	415	**556**	1	6.2	550
122	0	2.2		**292**	0	1.7		**425**	0	1.4	415	**557**	1	1.5	556
125	0	1.7	120	**297**	0	2.4		**427**	0	5.5	415	**559**	1	4	
127	0	0.6	47, 90, 125	**300**	0	1.2	297	**430**	0	3.8	417	**560**	1	6.5	516
130	0	4.4		**301**	0	1.2	300	**450**	1	4	420, 425, 427, 430	**562**	1	4.5	560
								452	1	1					

Table 10.1. Workcenter, duration and precedence constraints of each operation.

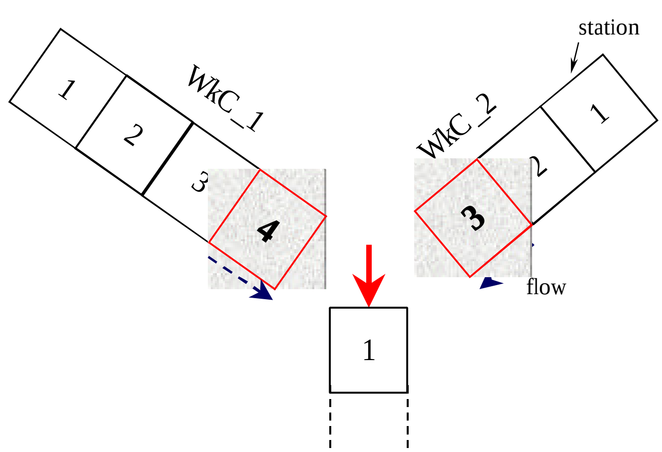

Table 10.2. Plant configuration corresponding to (NbS_1=4, NbS_2=3).

The hard constraint of this problem is the fixed number of stations. Thus, the number of stations of each workcenter was set between 1 and 4. Table 10.3 summarises the results of EPAL for different configurations of the assembly line. These results show that the presented method can deal with the multiple workcenter assembly line balancing (MWkCALB) problem (see Chapter 3), that is, it allows to balance the workload of the two workcenters using (or not) the different links between them. The author believes that the presented approach is a first step towards integrating the logical and the physical layout of assembly line.

The results, presented at Table 10.3, represent a set of solutions for a given number of stations, according to an equal piles strategy. (NbS_1, NbS_2) denotes the desired number of station of workcenter 1 respectively 2, the link represents the stations by which the two workcenters are connected, and finally WkC_1 (respectively WkC_2) represents the process time of stations for workcenter 1 (respectively 2). We give here only the results corresponding to (NbS_1=4, NbS_2=3), while the results corresponding to other configurations of the plant are summarised in Appendix 6.

The results show that by adding the link between the two workcenters, the whole line may be better balanced. For instance the stations workloads obtained in the case of (NbS_1=4, NbS_2=3), are:

- without link {WkC_1: 82, 82, 82, 82 and WkC_2: 73, 68, 58}
- with link {WkC_1: 75, 76, 75, 75 and WkC_2: 76, 76, 74}

Note, that the operation exchange between workcenters is only allowed at the connection station node. Operations from workcenter 1 can be mixed with some of workcenter 2. It is clear that the balancing obtained with link is better than those obtained without link. The same conclusion is made for the rest of results.

(NbS_1, NbS_2)	Link	WkC_1	WkC_2	(NbS_1, NbS_2)	Link	WkC_1	WkC_2
(1, 1)	no	329.6	200.7	**(3, 2)**	no	109.9, 109.9, 109.8	100, 100
	(1, 1)	265.4	264.9		(3, 2)	106.3, 106.3, 105.8	107.5, 104.6
(1, 2)	no	329.6	100, 100	**(3, 3)**	no	110.3, 109.8, 109.5	67.7, 53.3, 79.7
	(1, 2)	176.8	178, 175.5		(3, 3)	88, 88, 88	88, 89, 87
(2, 1)	no	164.8, 164.8	200	**(4, 1)**	no	82, 82, 82, 82	200
	(2, 1)	176.8, 176.7	176.8		(4, 1)	106, 106, 106, 105	106
(2, 2)	no	164.9, 164.7	100, 100	**(4, 2)**	no	82, 82, 82, 82	100, 100
	(2, 2)	132.8, 132.4	141.9, 123.2		(4, 2)	88, 87, 88, 88	92, 84
(2, 3)	no	194, 164,	73, 68, 58	**(4, 3)**	no	82, 82, 82, 82	73, 68, 58
	(2, 3)	106, 106	94, 106, 117		(4, 3)	75, 76, 75, 75	76, 76, 74
(3, 1)	no	109.9, 109.9, 109.8	200.7	**(4, 4)**	no	82.3, 82.4, 82.5, 82.4	56.8, 31.5, 68.7, 43.7
	(3, 1)	132.6, 132.6, 132.4	132.7		(4, 4)	66.3, 66.3, 66.4, 68.9	65.2, 55.8, 75.2, 66.2

Table 10.3. Station's workload for different line configurations.

Table 10.4 shows the results obtained for the two workcenters where the number of stations is set to four for the first workcenter (respectively three for the second). The table gives for each workcenter the process time of the different stations as well as their corresponding tasks. The first solution corresponds to the case where the two workcenters are not connected. The second workcenter is badly balanced because of the hard precedence constraints between tasks and the process time of the different tasks attributed to this workcenter. The architecture where the two workcenters are connected yields the second solution. The following tasks {127, 420, 427, 425, 292, 237, 395, 400, 402, 405} were transferred from the first workcenter to the second one. The second solution is better balanced over the two workcenter. The run time is under 10 minutes (on a PENTIUM II 333 MHz).

	WkC	PT	Ops
no link	0	82	180, 182, 185, 347, 257, 60, 240, 197, 193, 310, 410, 147, 297, 120, 135, 62, 22, 106, 417, 170, 122, 40, 190, 35, 252, 285, 65, 241, 355, 245
	0	82	415, 152, 300, 125, 155, 157, 70, 27, 225, 110, 130, 172, 430, 50, 162, 42, 312, 75, 112, 30, 132, 165, 87
	0	82	47, 90, 127, 280, 247, 367, 237, 350, 243, 265, 292, 387, 282, 338, 357, 420, 425, 305, 52, 137, 320, 337, 97, 335, 12, 117, 45, 301, 17, 55, 102, 332, 325, 302, 327
	0	82	427, 372, 380, 339, 397, 32, 67, 167, 307, 37, 20, 115, 15, 317, 287, 160, 322, 330, 100, 227, 140, 25, 395, 400, 402, 405
	1	73	450, 452, 455, 517, 520, 522, 525, 527, 530, 532, 535, 537, 540, 460, 457
	1	68	462, 465, 467, 470, 475, 477, 480, 482, 485, 487, 490, 507, 512, 515, 516
	1	58	550, 556, 557, 559, 562, 552, 555, 560, 542, 545, 547
with link	0	75	180, 182, 185, 60, 240, 147, 135, 297, 417, 130, 152, 137, 40, 245, 197, 27, 32, 397, 132, 355, 310, 252, 50
	0	76	193, 120, 62, 170, 190, 122, 162, 430, 155, 140, 115, 106, 227, 300, 287, 97, 327, 167, 320, 305, 65, 257, 285, 241, 325, 70
	0	75	330, 110, 165, 225, 322, 37, 372, 337, 243, 47, 90, 280, 247, 350, 282, 100, 75, 301, 67, 335, 317, 347, 367, 117, 410, 22
	0	75	338, 357, 415, 339, 332, 160, 17, 125, 52, 15, 20, 102, 172, 25, 302, 45, 307, 55, 265, 387, 30, 157, 112, 312, 380, 87, 12, 35, 556, 42
	1	76	450, 452, 455, 517, 520, 522, 525, 527, 530, 532, 535, 537, 540, 542, 545, 547
	1	76	457, 465, 467, 470, 475, 477, 480, 482, 485, 487, 490, 507, 512, 515, 516, 460, 462
	1	74	550, 557, 559, 560, 562, 552, 555, 127, 420, 427, 425, 292, 237, 395, 400, 402, 405

Table 10.4. Stations workload (NbS_1=4, NbS_2=3).

These results show that tacking into account the architecture of the assembly line can help to balance the different workcenters. The idea is to analyse the flow of products between workcenters and to use the links between them to allow transferring some tasks. This help to smooth the station's workload.

4.2. RP application : Car alternator

The chosen product is a car's alternator (Figure 10.6), corresponding to a real industrial case. The desired cycle time of the assembly line is fixed at *15* seconds. A description of the operations performed on product is summarised in tables Table 10.6, Table 10.7 and Table 10.8. A detailed description of the product with its main components is given in Appendix 7. Table 10.5 presents the precedence constraints between tasks.

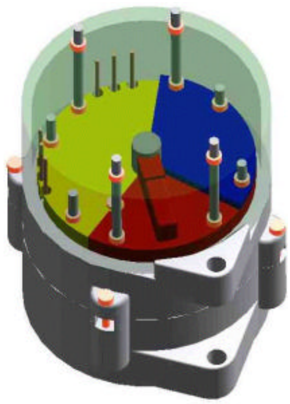

Figure 10.6. A view of the car alternator.

Op	Preds	Op	Preds	Op	Preds
1	4	**17**	16	**33**	32
2	1	**18**	6	**34**	31
3	2	**19**	17	**35**	33,34
4	-	**20**	19	**36**	35
5	3	**21**	20	**37**	22
6	10	**22**	21	**38**	31
7	-	**23**	17	**39**	36,38,46,47,48
8	-	**24**	17	**40**	39
9	-	**25**	18	**41**	40
10	7,8,9	**26**	16	**42**	41
11	10	**27**	44	**43**	42
12	10	**28**	45	**44**	29,30
13	11,12	**29**	28	**45**	20,23,24,25
14	13	**30**	28	**46**	35
15	14	**31**	27	**47**	35
16	15	**32**	31	**48**	35

Table 10.5. Precedence constraints of the product.

Table 10.6 presents for each task the possible resources to accomplish it and the operating mode M: manual, R: robotic and A: automated) associated to each equipment. For instance, task 1 can use one of the three pieces of equipment {0, 1, 2}, 0 being done manually, whilst 1 and 2 are automated FGs. Table 10.7 shows the process time and the cost of each equipment associated to a given operation. The last column in the table shows for each equipment the number of necessary operators (1 operator for manual tasks and 0 in case of machines or robots). The input data was prepared and structured using the SELEQ software package (Pellichero, 1999).

Op	MODE	EQUIP	Op	MODE	EQUIP	Op	MODE	EQUIP
1	M	0	**17**	R	25	**33**	A	49
	A	1		R	26		A	50
	A	2		R	27		A	51
2	M	3	**18**	M	28	**34**	A	52
	A	4	**19**	M	29		A	53
	R	5	**20**	A	30	**35**	A	54
3	A	6	**21**	A	31	**36**	A	55
	M	7		M	32	**37**	M	56
4	M	8	**22**	M	33	**38**	A	57
5	M	9	**23**	M	34	**39**	M	58
6	M	10	**24**	M	35	**40**	M	59
7	M	11	**25**	A	36		A	60
8	M	12		M	37		A	61
9	M	13	**26**	A	38		A	62
10	A	14		A	39	**41**	A	63
11	A	15	**27**	M	41	**42**	M	65
12	A	16	**28**	M	42	**43**	M	66
13	R	17	**29**	A	43	**44**	M	67
	R	18		A	44	**45**	A	68
14	R	19	**30**	A	45	**46**	A	69
	R	20		A	46	**47**	A	70
15	A	21	**31**	M	47	**48**	A	71
	A	22	**32**	M	48			
16	A	23						
		24						

Table 10.6. Operating mode and possible resources associated to each task.

Only two criteria are optimised in this example:

- imbalance of workload: the imbalance between the process time of the stations has to be minimised,
- cost: the price of the assembly line has to be minimised.

Note that the real number of stations cannot be determined by computing the ratio between the sum of the operating times and the cycle-time. Indeed, that number constitutes the theoretical minimum number of stations without considering the precedence constraints and the operating mode of the operations. The cycle time constraint is complied with by observing that there is a minimal/maximal duration for each task. The theoretical minimal (respectively maximal) number of stations is the sum of the duration of the fastest (respectively slowest) resource of each task over the cycle time. For the case presented here, the theoretical minimum number of stations is equal to 22, while the maximal number is 25.

In order to generate possible solutions, the following ICA presented in Chapter 7 is used. The MO-GGA was applied to this instance for several user's preferences. The results of the method are examined for different weight combinations corresponding to the relative importance one might give to each objective.

EQUIP	TIME	COST	NB_OP	EQUIP	TIME	COST	NB_OP
0	800	1712023	1	**35**	900	1700000	0
1	700	118396	0	**36**	400	80687	0
2	800	131218	0	**37**	500	1835082	0
3	400	1700000	1	**38**	1500	99613	0
4	200	100484	0	**39**	1400	476287	0
5	200	344492	0	**40**	900	1775000	1
6	400	466587	0	**41**	1500	1700000	1
7	1500	1795355	1	**42**	600	92387	0
8	300	1700000	1	**43**	700	468292	0
9	300	1700000	1	**44**	800	90403	0
10	300	1700000	1	**45**	800	468292	0
11	300	1700000	1	**46**	300	1700000	1
12	300	1700000	1	**47**	300	1700000	1
13	300	1700000	1	**48**	600	114550	0
14	1500	125000	0	**49**	600	488751	0
15	0	83931	0	**50**	700	198341	0
16	0	83931	0	**51**	400	10424	0
17	600	35915	0	**52**	400	45570	0
18	700	328029	0	**53**	1500	75000	0
19	600	18926	0	**54**	300	70000	0
20	700	471996	0	**55**	300	1700000	1
21	200	6473	0	**56**	1400	75000	0
22	300	384361	0	**57**	300	1700000	1
23	800	77318	0	**58**	1000	1700000	1
24	900	231324	0	**59**	500	79298	0
25	500	27659	0	**60**	500	81960	0
26	700	271667	0	**61**	600	457187	0
27	600	172932	0	**62**	1400	25000	0
28	400	1700000	0	**63**	1500	1700000	1
29	800	1700000	0	**64**	1500	1700000	1
30	800	45570	0	**65**	300	1700000	1
31	400	80687	0	**66**	1400	37500	0
32	500	1835082	0	**67**	400	70000	0
33	500	1700000	0	**68**	400	70000	0
34	500	1700000	0	**69**	400	70000	0

Table 10.7. Process time, cost (arbitrary units) and number of operators required by each equipment.

N	B	C	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	BALANCE	COST
22	0	1	**23**	22	15	12	15	13	13	12	14	15	14	18	14	**5**	15	15	14	16	15	14	15	15				254	22148352
22	0.5	0.5	15	15	15	15	14	13	14	**12**	12	14	15	14	18	14	15	15	14	**21**	15	14	15	15				74	23848352
22	1	0	15	15	15	15	15	15	14	**12**	13	14	15	15	18	14	15	15	15	**21**	15	14	15	15				62	29197448
23	0	1	**23**	22	15	14	13	4	**4**	8	12	14	14	15	14	23	10	15	15	14	16	15	14	15	15			513	22148352
23	0.5	0.5	10	14	15	12	15	14	13	13	12	14	14	15	14	**18**	14	**10**	15	15	16	15	14	15	15			93	24068032
23	1	0	15	15	15	15	15	15	12	**16**	14	14	15	15	12	15	14	**11**	15	15	14	13	14	15	15			44	28657204
24	0	1	15	9	**18**	15	14	13	14	12	12	14	15	12	6	18	10	15	15	14	15	11	**5**	14	15	15		312	22437168
24	0.5	0.5	10	14	15	12	15	14	13	**9**	13	12	14	**15**	14	12	14	10	14	15	15	15	13	14	15	15		132	25768032
24	1	0	15	15	**15**	15	14	15	14	12	13	14	15	13	**7**	15	11	11	15	15	14	13	15	14	15	15		122	30675056
25	0	1	12	9	**21**	15	4	14	13	9	13	12	14	15	14	18	**4**	5	14	10	15	15	16	15	14	15	15	516	22355208
25	0.5	0.5	14	7	15	9	**15**	14	13	13	13	12	14	15	14	12	**4**	14	10	14	15	15	13	15	14	15	15	287	27248352
25	1	0	14	**8**	15	12	15	14	12	12	9	13	13	14	15	15	11	15	11	**15**	15	14	13	15	14	15	15	161	33150960

Table 10.8. Process time of each station according to the different weights (B, C).

Table 10.8 summarises the results, obtained in less than 10 minutes (on a PENTIUM II 333 MHz). It presents the process time on the different stations, the total cost of the line according to the different optimisation strategies. The number of stations is given by *N*, the cost of the line by "COST" and the balancing by "BALANCE". The columns labelled from 1 to 25 represents the workload of the different stations. Number within circles represent stations where the cycle time is exceeded. The weight attributed to the balancing is '*B*', the one for cost being '*C*'. The weights (B, C) represent the relative importance given to each criterion. In this case, three pairs of preferences which are {(0, 1),(1, 0), (0.5, 0.5)} were used. The pair (0, 1) means that the cost is the only important objective, no care is given to the imbalance of the line. In contrast, the pair (1, 0) means the opposite. Finally, the pair (0.5, 0.5) means that the same importance is given to the two objectives.

The algorithm was run 12 times using four different *N* "number of stations" (*N* varying from the theoretical minimum number of stations to the theoretical maximal number) and three combinations of preferences. For a given number of stations the three cases were studied. The results show that the proposed method respects the user's preferences regarding the optimisation objective. Figure 10.7 shows the cost of the line according to the number of stations for several preferences. It demonstrates that the increase of the cost with the number of stations is not a general behaviour. For instance the cost of a line with 23 stations is less than with 22 stations (for weights set to (1, 0)). For a given number of stations, the cost of the line corresponding to (1, 0) is high in comparison with (0.5, 0.5) which is higher than the cost corresponding to (0, 1).

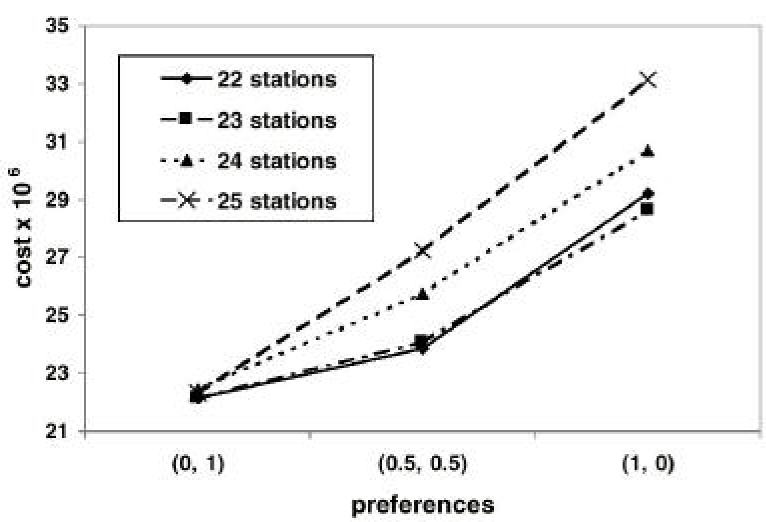

Figure 10.7. Cost (arbitrary units) of the line according to three preferences.

The results corresponding to the solutions with 24 stations allow to make the following comments:

- the couple (B = 1, C = 0) yields a minimal process time of 7 (station 13) and the maximal process time of 15 and a cost of 30675056.

- the couple (B = 0.5, C = 0.5) yields a minimal process time of 9 (station 8) and the maximal process time of 15 and a cost of 25768032.
- the couple (B = 0, C = 1) yields a minimal process time of 5 (station 21) and the maximal process time of 18 (station 3) and a cost of 22437168.

The preference (1, 0) yields an expensive but well balanced line in comparison to other preferences (see Table 10.8). In contrast, the results obtained using the preference (0.5, 0.5) show clearly that setting an equal weight to the two objectives does not mean that one will obtain the line with the lowest cost and the lowest imbalance simultaneously, but rather the best compromise between the two objectives. Finally, the couple (0, 1) leads to a cheapest (minimal cost) and a less balanced line.

Figure 10.8 shows that the preference (1, 0) leads to a good balancing in comparison to the other ones. Since the two objectives (cost and imbalance) are conflicting, improving the quality of one of them decreases the quality of the other. The preference given to the different objectives permits to the algorithm to explore several regions of the search space.

The station load can exceed the cycle time in some cases, meaning that the desired cycle time cannot be held for the selected number of stations. The line will generally be less expensive as the cycle time constraint is relaxed. These results show that a solution using 22 stations leads to the cheapest cost if the balancing is not important. Even if the cost of this solution is very small, the process time of some stations exceeds the cycle time (for instance, 23 seconds for station 1) and the quality of the balancing is so poor that this solution will never be accepted in practice. The choice of a solution is user-dependent. A good compromise between the balancing and the cost of the line corresponds to a solution using 24 stations found using the (0.5, 0.5) preference.

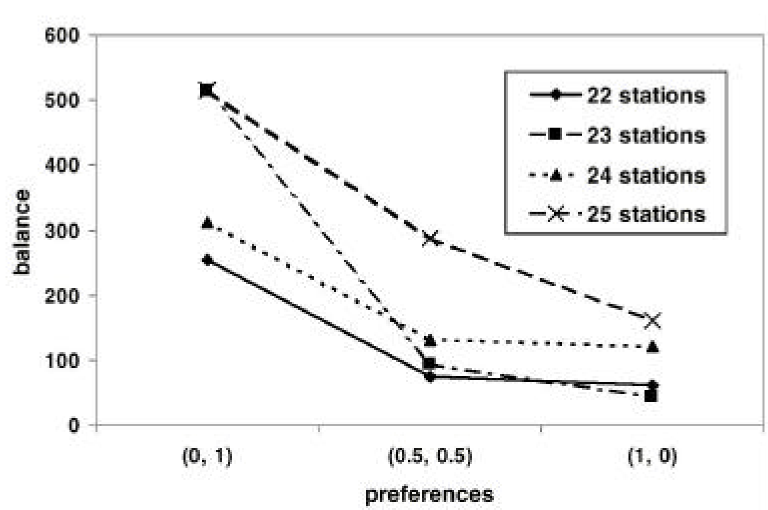

Figure 10.8. Balancing of the line according to the preferences set for different number of stations.

The three combinations of weights analysed show that obtaining a solution having simultaneously the lowest cost and the lowest imbalance is not possible in the proposed instance of the problem. It has also clearly demonstrated that considering each criterion separately leads to very bad results according the other ones. Giving the same preference to the two objectives leads to solutions where the values obtained for each criterion are a good compromise between the two others.

The main advantage of such a computer-aided tool is that it allows to try a lot of different combinations for a lot of different sets of data. This is almost impossible to realise manually due to the very large amount of possible solutions. An important aspect of this approach is that the decision maker stays the master of the optimisation process.

5. Conclusions and further works

In this chapter an interactive and iterative approach to design assembly line is presented. The approach deals with the different features of assembly line. The author presented a methodology for the design of product and its assembly line. It is important to note that the approach is a concurrent one, as it is the line balancing or physical layout of the line that finally fixes the assembly sequence of the product. The aim is to give designers a set of quick tools and a methodology to perform the design of their line starting from a product preliminary design and to allow them testing several alternatives. A main feature of the methodology is that all the proposed tools may be used independently. Another important aspect of these tools is that the user stays at any moment the master of the design process.

The architecture of the proposed method shows that wishes coming from the industrial world can be taken into account. The author believes that the method is able to deal with real-world problems, but it still needs more tests and confrontations to industrials 'point of view.

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