

Supplementary materials

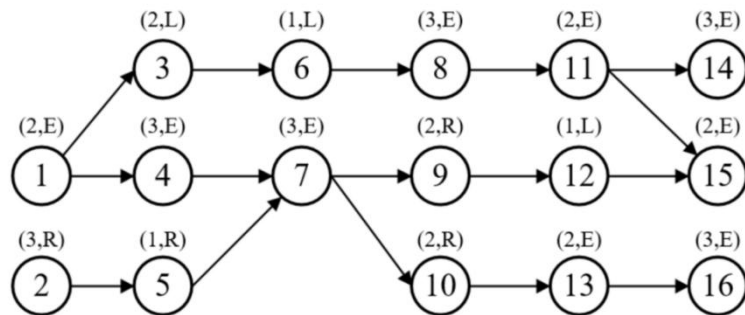


Fig. 1. Precedence and direction constraint diagram of P16.

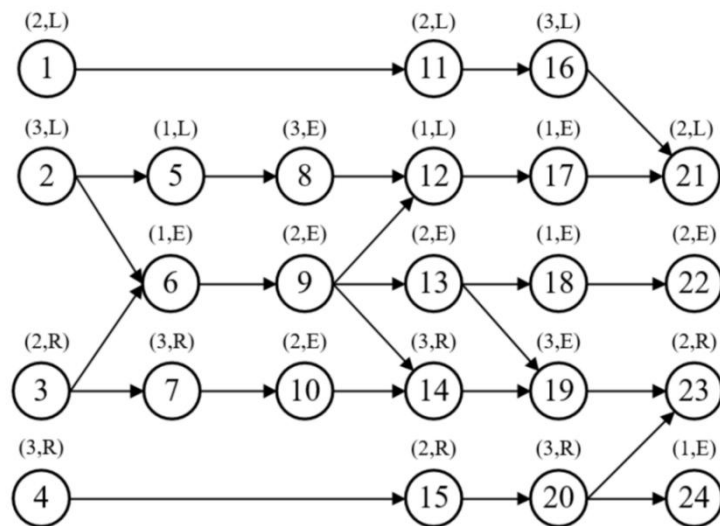


Fig. 2. Precedence and direction constraint diagram of P24.

Table 1

Precedence and direction constraints table of P65.

Task	Side	Task time	Immediate successors
1	E	2	3
2	E	3	3
3	E	2	4,23
4	E	3	5,6,7,9,11,12,25,26,27,41,45,49
5	E	1	14
6	E	1	14
7	R	3	8
8	R	3	14
9	L	2	10
10	E	2	14
11	E	2	14

12	E	1	14
13	E	2	14
14	E	3	15,18,20,22
15	E	2	16
16	L	3	17
17	L	2	31
18	R	3	19
19	R	2	21
20	E	3	21
21	E	1	31
22	E	1	31
23	E	3	24
24	E	3	31
25	L	2	31
26	R	2	31
27	R	2	28
28	R	1	50
29	L	2	50
30	L	3	50
31	E	2	32,36,51,52,53,54,55,56,58,59,60,61,62
32	E	3	33
33	E	2	34
34	E	3	35
35	R	2	50
36	E	3	37
37	E	1	38
38	E	1	39,40
39	L	3	50
40	R	3	50
41	E	2	42
42	E	2	43
43	E	2	62
44	R	1	46
45	L	2	46
46	E	3	47
47	L	2	48
48	L	3	50
49	E	2	50
50	E	3	65
51	R	2	65
52	E	3	65

53	L	1	65
54	E	1	65
55	R	3	65
56	E	3	57
57	E	2	65
58	L	2	65
59	R	2	65
60	E	1	65
61	R	2	65
62	E	3	65
63	L	2	64
64	L	3	65
65	E	2	

Table 2

Ten Pareto-optimal solutions for instance P24 selected based on crowding distance.

Algorithm	Case	f1	f2	f3	Algorithm	Case	f1	f2	f3
IMOMBO	1	8.9	3.2841	8.9938	MOMBO	1	10.2	2.8432	9.6603
	2	10.9	2.9216	7.4128		2	11.4	2.7008	7.8105
	3	11.1	2.6225	8.8179		3	12.3	2.9034	4.4211
	4	12.4	3.3182	2.6908		4	13.9	2.3316	10.5764
	5	13.6	2.6982	3.1780		5	14.8	2.3533	5.4799
	6	14.2	3.1665	0		6	15.0	1.8220	12.2628
	7	15.4	2.1422	6.2392		7	16.4	1.0884	14.4493
	8	16.0	1.0549	14.9609		8	16.8	0.7973	15.3147
	9	16.9	0.3706	17.7032		9	17.8	0.6940	16.7555
	10	20.2	0.3121	18.3299		10	19.6	1.7220	9.6653
MOABC	1	10.2	2.9209	9.5397	NSGA-II	1	10.5	2.4284	10.8228
	2	11.6	2.7556	7.3837		2	11.1	2.8726	10.0347
	3	14.7	2.2472	5.3760		3	13.1	2.4789	6.1616
	4	21.8	0.1344	18.5287		4	13.5	3.2661	0
	5	27.4	0.7679	11.3878		5	14.4	2.8139	2.6244
	6	28.9	0.1919	20.9762		6	17.0	0.9512	15.9229
	7	32.3	1.3341	0		7	18.9	2.0377	4.1328
	8	35.6	0.3681	13.6329		8	19.1	1.1026	13.4989
	9	36.5	0.1344	18.5287		9	19.8	2.0377	4.1328
	10	37.7	0.1529	20.2893		10	21.9	0.2813	18.6657

Table 3

Ten Pareto-optimal solutions for instance P65 selected based on crowding distance.

Algorithm	Case	f1	f2	f3	Algorithm	Case	f1	f2	f3
IMOMBO	1	27.1	3.3932	29.6468	MOMBO	1	29.4	2.6672	27.9831
	2	30.2	2.8228	27.0526		2	30.4	2.7185	26.8265
	3	32.0	2.3455	31.8352		3	33.0	2.3594	27.9012
	4	34.4	2.6357	9.9461		4	35.0	1.7724	32.9770

MOABC	5	37.9	2.1486	21.4388	NSGA-II	5	37.9	2.0641	28.7639
	6	38.4	1.7091	28.4763		6	39.0	1.8352	29.8968
	7	38.4	3.2592	0		7	42.7	2.6831	0
	8	40.9	1.1948	35.3894		8	43.4	1.4959	29.2822
	9	43.9	0.5930	46.8470		9	45.8	1.2345	28.4959
	10	50.5	0.4603	46.0538		10	49.3	0.9737	31.6442
	1	28.9	2.9669	29.4191		1	27.6	3.3080	27.2217
	2	33.3	2.4110	29.7684		2	33.9	2.2174	29.2782
	3	36.2	2.4244	23.0218		3	35.2	2.5458	23.6276
	4	38.5	1.6710	28.9739		4	36.9	1.5419	34.0173
	5	41.7	2.7791	0		5	39.6	1.1207	38.8395
	6	43.1	0.6310	47.7028		6	41.9	2.7344	0
	7	45.4	0.6236	45.3362		7	43.1	1.0975	35.1047
	8	51.0	0.4161	49.5669		8	46.4	0.7392	41.4472
	9	66.3	0.5938	32.4084		9	50.1	1.4007	16.2045
	10	86.3	0.0812	56.8162		10	53.5	0.4040	48.1361

Table 4

Task name, precedence, direction, operation time, and fatigue index in the case study.

Task	Description of task	Predecessor	Type	Time	Fatigue index
1	Install Connecting Rod Component	-	E	6	0.2
2	Install Oil Cylinder Foundation	-	L	5	0.2
3	Install Crankshaft	-	E	4	0.2
4	Attach Connecting Rod Cap	1	E	2	0.3
5	Tighten Connecting Rod Bolt and Oil Cylinder Foundation Bolt	1,2	E	6	0.1
6	Install Crankshaft Bearing Cap	-	E	4	0.3
7	Tighten Crankshaft Bearing Cap Bolt	3,4	L	4	0.4
8	Install Cylinder	5	E	4	0.1
9	Mount Timing Chain onto Crankshaft	3	R	3	0.4
10	Install Chain Constraint Mechanism	6	R	8	0.2
11	Tighten Cylinder Bolt and Chain Constraint Bolt	7,9	E	2	0.4
12	Install Side Cylinder Head	7	E	6	0.3
13	Perform Alignment Check for Crankshaft Assembly	8	L	7	0.4
14	Install Upper Cylinder Head	10	E	3	0.1
15	Assemble Valve Component	9	R	5	0.2
16	Install Rocker Arm	12	E	6	0.5
17	Tighten Upper Cylinder Head Bolt	13,14	E	2	0.4
18	Install Spark Plug	-	R	7	0.2
19	Secure Valve Component	15	E	5	0.3
20	Secure Rocker Arm	16	R	2	0.4
21	Install Camshaft	19	E	9	0.5
22	Install Camshaft Cover Sheet	-	L	1	0.2

23	Attach Cranking Claw	18	R	3	0.1
24	Secure Camshaft	20	R	7	0.5
25	Install Camshaft Cover	19	E	5	0.2
26	Tighten Camshaft Cover Sheet Bolt	22	E	5	0.3
27	Install Pulley	23	E	5	0.3
28	Tighten Camshaft Cover Bolt	21	L	3	0.2
29	Mount Flywheel	17,24	E	2	0.4
30	Secure Flywheel Bolt	25	E	5	0.4
31	Tighten Flywheel Nut	26	L	5	0.3
32	Assemble Chain Constraint Final Check	26,27	E	4	0.3
33	Check Timing Chain Tension and Alignment	28,29	E	7	0.2
34	Manual Rotation Test for Crankshaft and Camshaft	32	E	3	0.4
35	Apply Lubricating Oil to Friction Surfaces	31,33	E	6	0.4
36	Final Fastening Check for All Bolted Connections	34	E	8	0.3

Table 5

Optimal assembly configuration under cycle time preference.

Scenario 1 (CT=28.2, ER=4.2029, EC=17.2938)

Station	Operator	Task	st	t	ft	Station	Operator	Task	st	t	ft
1	Human 4	1	0.0	5.1	5.1	2	Human 5	14	0.0	2.3	2.3
Left Side		2	5.1	2.9	8.0	Right Side		8	9.2	2.7	11.9
		3	8.0	4.6	12.6			27	11.9	3.2	15.1
		4	12.6	1.4	14.0			15	15.1	3.5	18.6
		22	14.0	1.8	15.8			12	18.6	3.9	22.5
		26	15.8	3.5	19.3		Robot1	19	2.3	6.9	9.2
1	Human 6	6	0.0	3.2	3.2			8	9.2	2.7	11.9
Right Side		18	3.2	5.3	8.5			27	11.9	3.2	15.1
		10	8.5	8.4	16.9			15	15.1	3.5	18.6
		9	16.9	1.6	18.5			12	18.6	3.9	22.5
		23	18.5	4.2	22.7	3	Human 3	21	0.0	6.2	6.2
2	Human 2	5	0.0	3.2	3.2	Left Side		25	6.2	4.8	11.0
Left Side		7	3.2	5.2	8.4			28	11.0	4.2	15.2
		31	8.4	3.4	11.8			30	15.2	5.3	20.5
		13	11.5	4.8	16.3			36	20.5	6.7	27.2
		11	16.2	1.3	17.5			29	27.2	1.0	28.2
	Robot 3	31	8.4	3.4	11.8	3	Human1	16	0.0	3.7	3.7
		13	11.5	4.8	16.3	Right Side		34	3.7	1.8	5.5
		11	16.2	1.3	17.5			20	5.5	1.2	6.7
		32	17.5	5.3	22.8			24	6.7	4.4	11.1
		17	22.8	2.6	25.4			33	15.2	4.5	19.7
								35	19.7	7.4	27.1
							Robot 2	16	0.0	3.7	3.7

34	3.7	1.8	5.5
20	5.5	1.2	6.7
24	6.7	4.4	11.1
33	15.2	4.5	19.7

Table 6

Optimal assembly configuration under workers ergonomic risk preference.

Scenario 2 (CT=53.2, ER=0.7087, EC=36.8032)

Station	Operator	Task	st	t	ft	Station	Operator	Task	st	t	ft
1	Robot 1	1	0.0	8.3	8.3	2	Human 3	8	0.0	2.4	2.4
Left Side		2	8.3	6.7	15.0	Right Side		14	2.4	4.4	6.8
		3	15.0	5.4	20.4			15	6.8	3.7	10.5
		6	20.4	5.2	25.6			27	10.5	6.9	17.4
		22	25.6	1.4	27.0			19	17.4	3.4	20.8
		4	27.0	2.6	29.6			12	20.8	3.8	24.6
1	Human 1	18	0.0	4.6	4.6	3	Robot 3	16	0.0	8.1	8.1
Right Side		10	23.6	9.9	33.5	Left Side		25	8.1	6.6	14.7
		9	33.5	4.2	39.7			28	14.7	4.2	18.9
		5	39.7	6.2	45.9			29	24.5	2.7	27.2
		23	45.9	2.7	48.6			33	27.2	9.2	36.4
		26	48.6	4.6	53.2			35	36.4	7.8	44.2
2	Robot 2	7	0.0	5.5	5.5	3	Human 5	17	0.0	2.8	2.8
Left Side		31	5.5	6.8	12.3	Right Side		34	2.8	3.8	6.6
		13	12.3	9.6	21.9			20	8.1	2.5	10.6
		11	21.9	2.8	24.7			30	14.7	2.8	17.5
		32	24.6	5.3	30.0			24	17.5	7.0	24.5
		21	30.0	12.4	42.4			36	24.5	9.8	34.3

Table 7

Optimal assembly configuration under cbots energy consumption preference.

Scenario 3 (CT=35.4, ER=3.9550, EC=6.0843)

Station	Operator	Task	st	t	ft	Station	Operator	Task	st	t	ft
		k									
1	Human 3	2	0.0	5.7	5.7	2	Human 5	8	0.0	3.8	3.8
Left Side		3	5.9	2.5	8.4	Right Side		14	3.8	2.3	6.1
		6	8.3	2.8	11.1			15	6.1	4.1	10.2
		22	11.1	0.7	11.8			19	10.2	6.1	16.3
		4	11.8	2.4	14.2			11	16.3	2.4	18.7
		26	14.2	3.7	17.9			21	18.7	5.0	23.7
		7	17.9	4.8	22.7	3	Human 4	16	0.0	3.2	3.2
		12	22.7	3.8	26.5	Left Side		17	3.2	2.2	5.4
	Robot 3	3	5.9	2.5	8.4			25	5.4	6.4	11.8
		6	8.3	2.8	11.1			34	11.8	1.8	13.6
		22	11.1	0.7	11.8			30	13.6	6.9	20.5
1	Human 6	1	0	7.1	7.1			28	20.5	2.0	22.5

Right Side		18	7.1	5.3	12.4			29	17.9	6.9	24.8
		9	12.4	1.6	14.0	Robot 1		34	11.8	1.8	13.6
		10	14	8.4	22.4			30	13.6	6.9	20.5
		5	22.4	7.9	30.3			28	20.5	2.0	22.5
		23	30.3	4.2	34.5	3	Human 1	20	3.2	2.6	5.8
2	Human 2	27	0.0	6.7	6.7	Right Side		24	5.8	7.0	12.8
Left Side		31	6.7	5.5	12.2			36	13.6	8.9	22.5
		13	12.2	10.2	22.4			33	22.5	5.5	28.0
		32	22.4	5.5	27.9			35	28.0	7.4	35.4