A Practical Approach to solving Multi-objective Line Balancing Problem

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Proplanner

Agenda

- Introduction & Examples
- Objectives & constraints
- Academic versus Industry focus
- Solution approaches
- Mixed Model Balancing
- Operator Constraints
- Effect of MPM on Line Balancing
- References & Resources

Assembly Line Balancing Problem

- *The decision problem of optimally partitioning (balancing) the assembly work (tasks) among the stations with respect to some objective is known as the assembly line balancing problem (ALBP)*
- Tries to achieve the best compromise between labor, facility and resource requirements to satisfy a given volume of production
- Characteristics
  - NP hard problem - existing optimization procedures have a complexity of at least 2^N
  - Usually a multi-objective problem
  - Reduces to the traditional bin-packing problem if task precedence constraint is removed
- Common formulation
  - Given set of tasks, precedence graph of tasks and cycle time, solve for number of stations
  - Cycle time bounds: $\max_{i=1,\dots,N} t_i \le \max_{j=1,\dots,K} s_j \le c \le 1/D$
- Long - Mid term strategic problem in assembly line design

ALBP – Illustrative Example

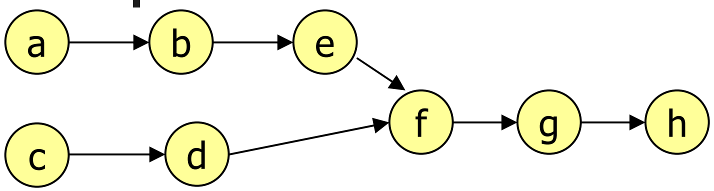


Figure 1: Precedence Graph for an assembly process

Task	Description	Task Time (minutes)
a	Position controller lowing housing	**0.2**
b	Position bimetal coil	**0.2**
c	Attach power cord from heating unit	**0.8**
d	Position controller upper housing	**0.6**
e	Attach male plug to line cord	**0.3**
f	Attach fuse to line cord	**1.0**
g	Affix logo	**0.4**
h	Seal controller housing	**0.3**
	Total Time	**3.8**

Figure 2: Task times

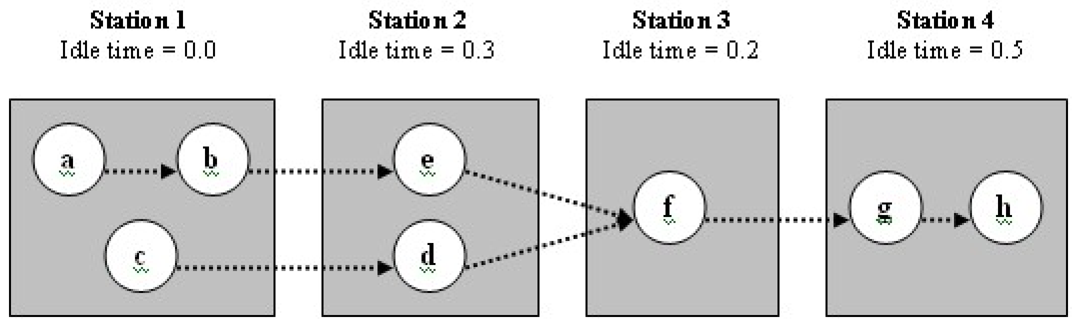


Figure 3: Assignment of tasks for a cycle time of 1.2 minutes

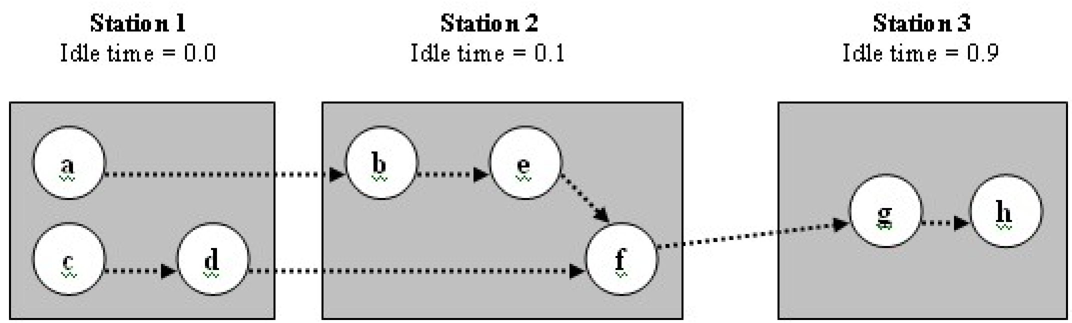
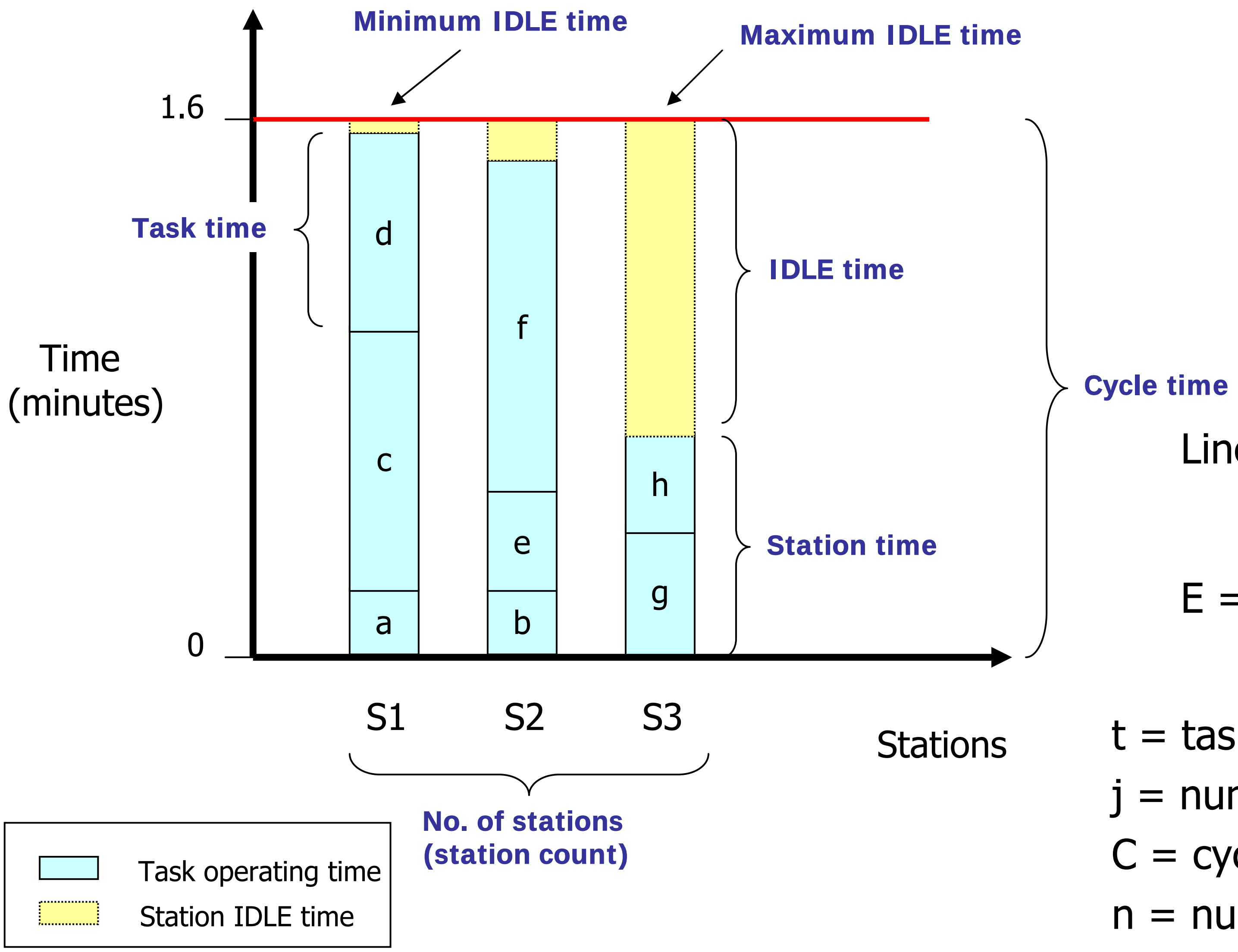


Figure 4 Assignment of tasks for a cycle time of 1.6 minutes

Note: Minimum possible cycle time = 1 min

Measures used in ALBP



Line Efficiency

$$E = \frac{\sum_{i=1}^{j} t_i}{nC}$$

t = task time for i

j = number of tasks

C = cycle time

n = number of stations

Objectives used in ALBP

- Base Objective - Capacity related objectives (90%)
  - Type 1: Minimize number of stations given cycle time
  - Type 2: Minimize cycle time for given number of stations
  - Type F: Given cycle time & number of stations determine feasibility
  - Type E: Minimize both cycle time & number of stations
- Problem Type - Line Design
  - Single, Mixed or Multi-Model Lines
  - Simple, Parallel or U-Lines
- Multi-Objective problems - Constraints modeled as objectives
  - For example, determining number of fixed & floating operators
  - Minimize operator delays (IDLE)
  - Minimize assignment of tasks to one side of the line
  - Minimize resource violations on the line

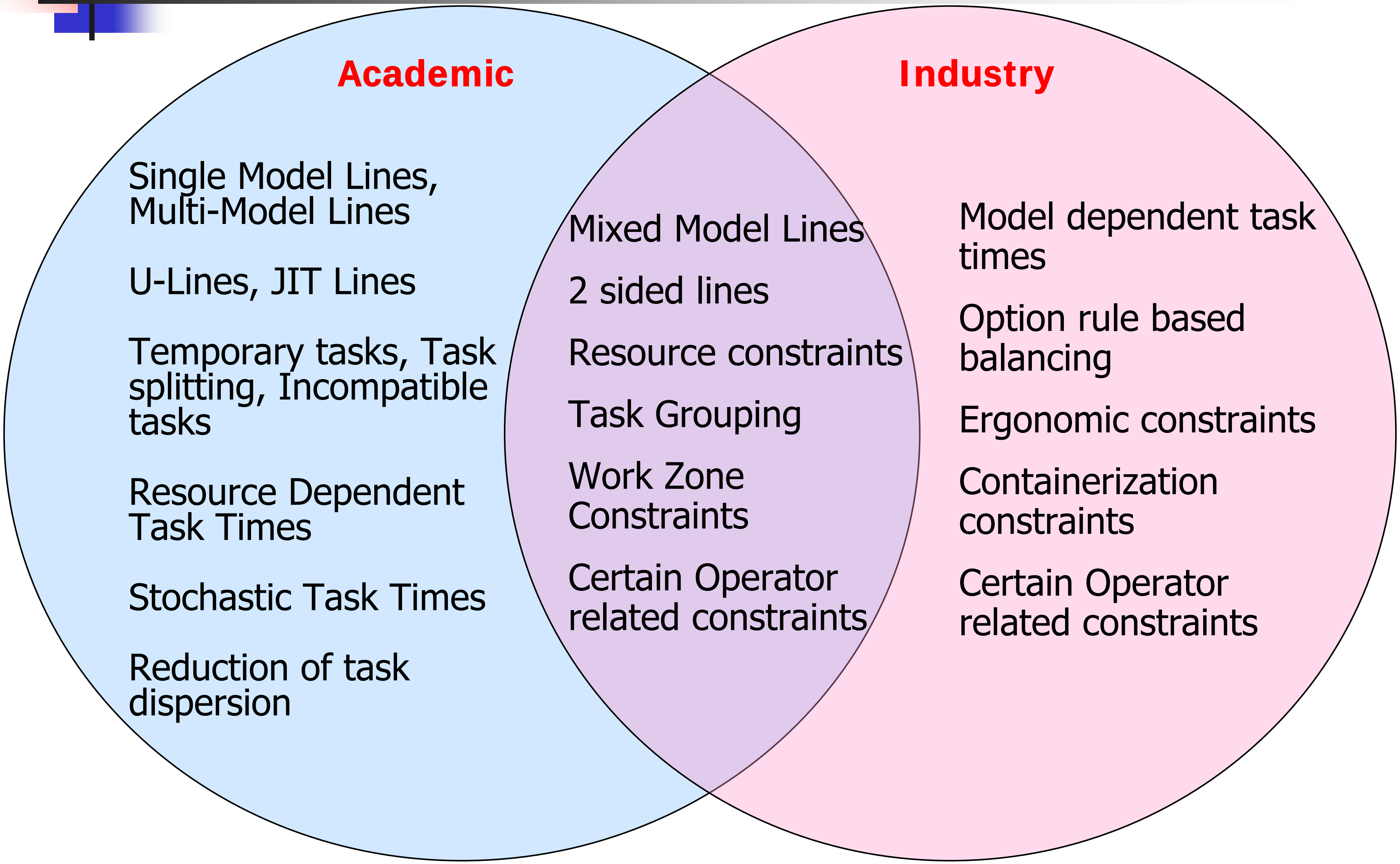
Constraints used in ALBP

- Task Grouping
- Resource Dependent Task Times
- Stochastic Task Times
- Task splitting
- Incompatible Task Assignments
- Temporary tasks with unknown durations
- Work Zone (line side) related constraints
- Containerization constraints
- Operator related constraints
- Ergonomic constraints
- Reduction of work overload
- Reduction of task dispersion
- Printed circuit board (PCB) and Robotic line constraints
- Throughput improvement and scrap reduction
- Balancing U shaped JIT lines (The N U-line balancing problem)
- Dynamic line balancing (DLB)

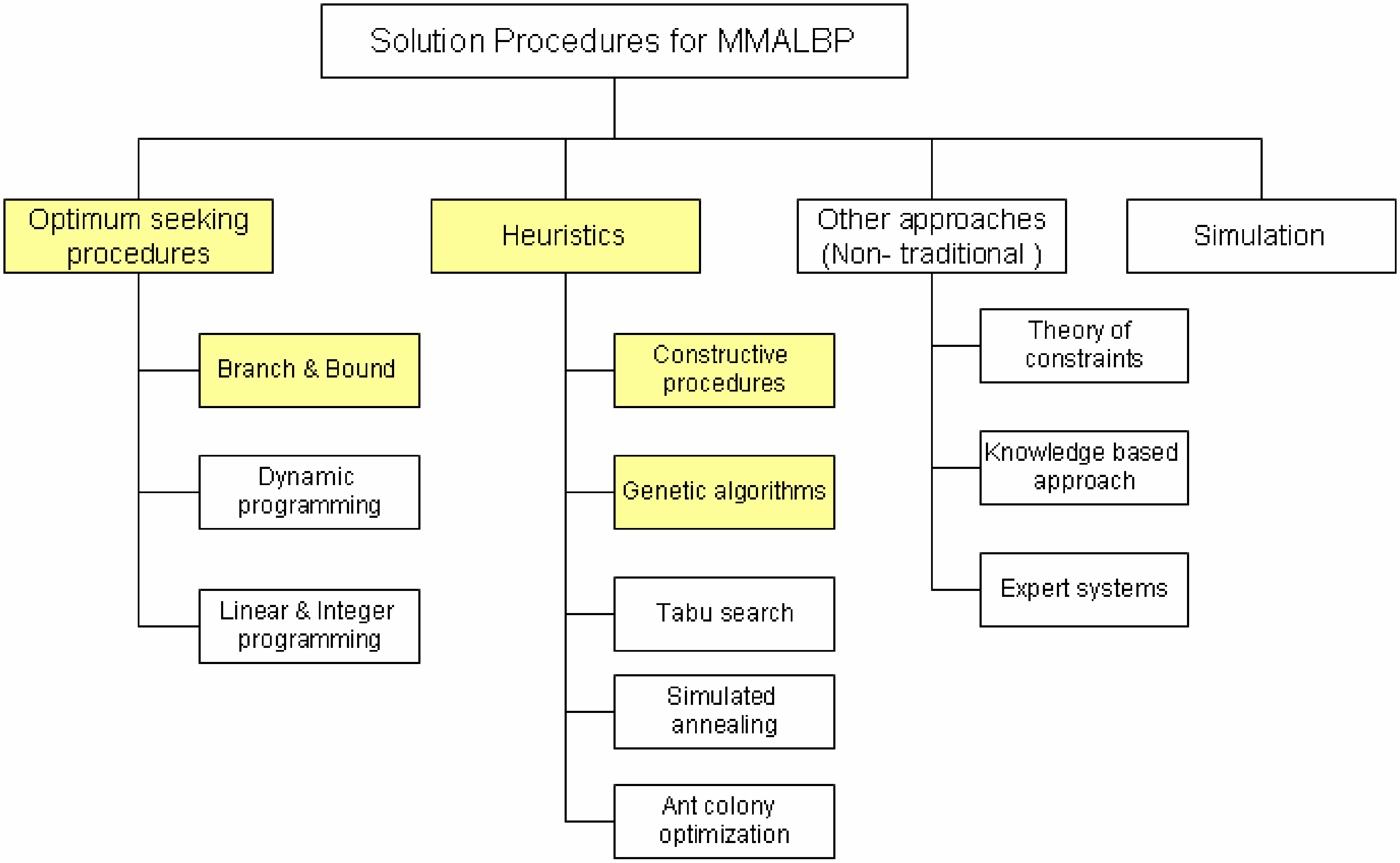
Academic vs. Industry Focus

- A “Gap” exits between Academic & Industrial worlds
- Possible reasons
  - Researches tend to model simple problems with convenient assumptions to aid in solving & benchmarking solutions.
  - Focus is on ”optimality” rather than on “practicality” – Need to consider cost of optimality.
  - Scientific results could not be transferred back to practical applications – Problems not generic.
  - The problems were covered, but could not be solved to satisfaction.
  - Line Balancing is not the only manufacturing problem to solve – Time limitations in the practical world limits good analysis

Academic vs. Industry Focus



Solution Approaches



Work Definition

- Operations-Routings
  - Collection of tasks assigned to Operator/Station
- Tasks
  - Smallest amount of movable work
  - Owns Parts, Tools, Time, Workzone, Model, Option, Ergo, Instructions
  - May be Grouped and Clustered
- Elements
  - Lowest level of definable work (pick, place, walk, turn, etc)

COMSOAL Algorithm

- Computer Method for Sequencing Operations for Assembly Lines.
- Developed as part of an industrial OR project in 1966 & later implemented at Chrysler.
- A simple record keeping procedure that uses several lists for speed computation
- Why COMSOAL ?
  - Simplifies complex assembly line problems – Easy to understand & implement.
  - Faster, easier, and more accurate than calculating by hand.
  - Multiple objectives & constraints could be modeled into the algorithm easily.
  - Solution quality could be improved by increasing the iterations – today’s computing power makes this easy

COMSOAL Procedure (Type 1)

- Given TAKT, find min(N stations) which will max(Utilization)
- Step 1: Initialize lists & variables
  - Cycle Time : C
  - Stopping criteria or Upper Bound: UB
- Step 2: Start New Iteration
  - LIST A – Set of all tasks
  - NIP – 2D array containing number of immediate predecessors for each task i in LIST A
  - Set current station count, N = 1
- Step 3: Precedence Feasibility
  - Compute LIST B : For all task $i \in A$, add i to B if NIP(i) = 0
- Step 4: Time Feasibility
  - Compute LIST C: For all task $i \in B$, add i to C if $t_i <= (C - S_n)$, where t_i is task time & S_n is station time
  - If Count (C) = 0, go to Step 5, else Step 6

COMSOAL Procedure cont…

- Step 5: Open New Station
  - N = N +1
  - Check for UB or metric & return to Step 7 if the current iteration is not feasible; Otherwise go to Step 3
- Step 6: Assign task to station
  - Select task from LIST C
    - Random selection or apply selection criteria / heuristic
  - Update station time Sn.
  - Remove select task i from A, B & C. Update NIP
  - If Count(A) = 0, go to Step 7, else Step 3
- Step 7: Schedule Completion
  - Compute the required metric such as Total IDLE, violation count, line efficiency etc.
  - If computed metric is better than previous best store current solution as BEST solution.
  - Check for stopping criteria & stop. Otherwise go to Step 2 (new sequence).

COMSOAL Procedure (Type 2)

- Fundamental in use for Improvement
- Given N stations, find min(TAKT) to max(util)
- Solving Type 2 problems
  - Compute C_{min} & C_{max}
    - $C_{min} = \max\{t_{max}, [t_{sum}/N]\}$, where t_{max} is maximum task time, t_{sum} is sum of all task times
    - $C_{max} = 2 * C_{min}$
  - Run Type 1 COMSOAL for $C \in [C_{min}, C_{max}]$ such that $N_{result} \leq N_{given}$.
  - Search could be minimized by checking for N values in Step 5 (while opening new stations).
  - If no solution is found, increase C_{max} and repeat search.

COMSOAL for Resource Constraints

- Resource Constraint:
  - Each station has a fixed list of resources: $S_R(i)$
    - S1 = {R1, R2,..}, S2 = {R1, R3, …}
  - Each task has a fixed list of resource it requires/uses: $T_R(i)$
    - T1 = {R1}, t2 = {R1, R2}
  - Assign tasks to station such that the resource requirements of tasks are satisfied.
  - Monumental vs. Ordinary Resources
  - Modeling as Objective vs. as a constraint
    - Monumental resources are usually modeled as hard constraint
- COMSOAL Modification – As an objective
  - Step 7: Compute the number of resource violations R_V
  - Solution quality could be compared by a rule such as

    "least number of stations, followed by least violation count"

    or,

    a weight could be assigned to station count objective & resource objective
- COMSOAL Modification – As a constraint:
  - Include an additional step.
  - Step 4.5 - Resource Feasibility: Compute LIST D from LIST C, such that all resources $R \in T_R(i)$, is also $\in S_R(i)$

Improvement vs Construction

- Construction
  - Recreates balance of tasks among affected stations
  - Causes many unnecessary (cost) task moves
- Improvement
  - Provides ability to select range of tasks at selected stations
  - Provides ability to remove or add stations
  - Type 2 Comsoal is run on reduced data set find alternatives
  - Additionally, pairwise interchange is employed to evaluate minimal change for maximum benefit

Mixed Model Balancing

- Mixed model assembly lines (MMAL) manufacture several models (variants) of a standard product in an intermixed sequence

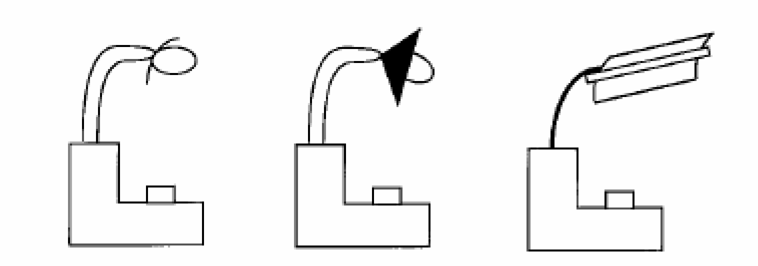


Figure 1: Example of product variants (models)*

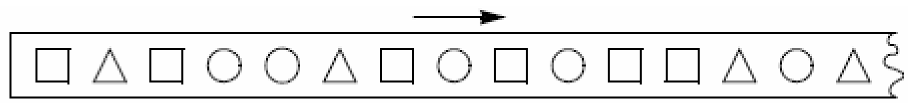


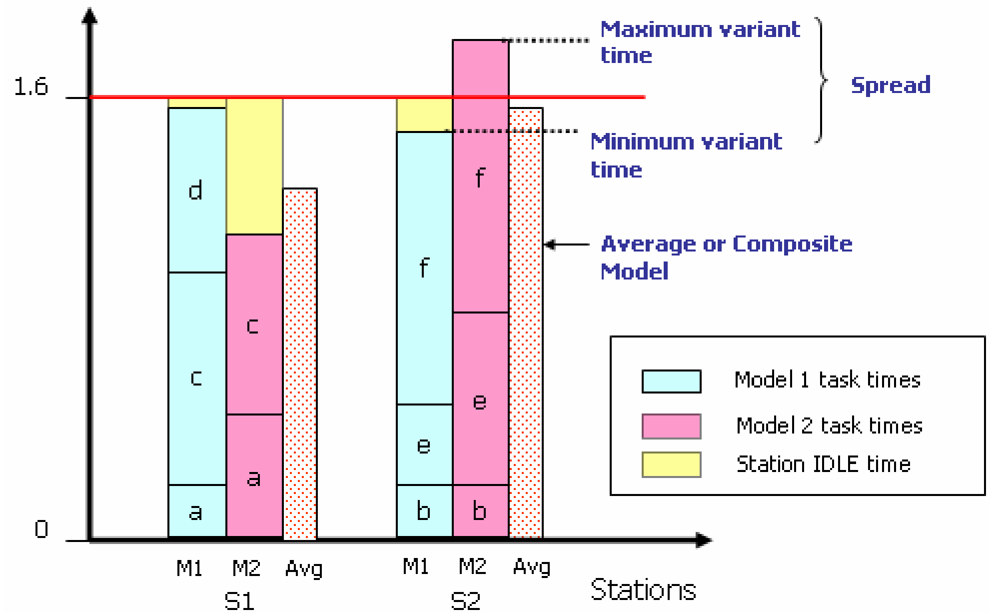
Figure 2: Example of intermixed sequence **

- Mixed Model Balancing assigns operations to stations so that station loads are balanced across models
  - variation in station loads should be minimal across models
- Common Formulation
  - Given weighted task times, combined precedence, shift time

$$\text{minimize} \sum_{i=1}^{n} (TT - TT_{si})$$

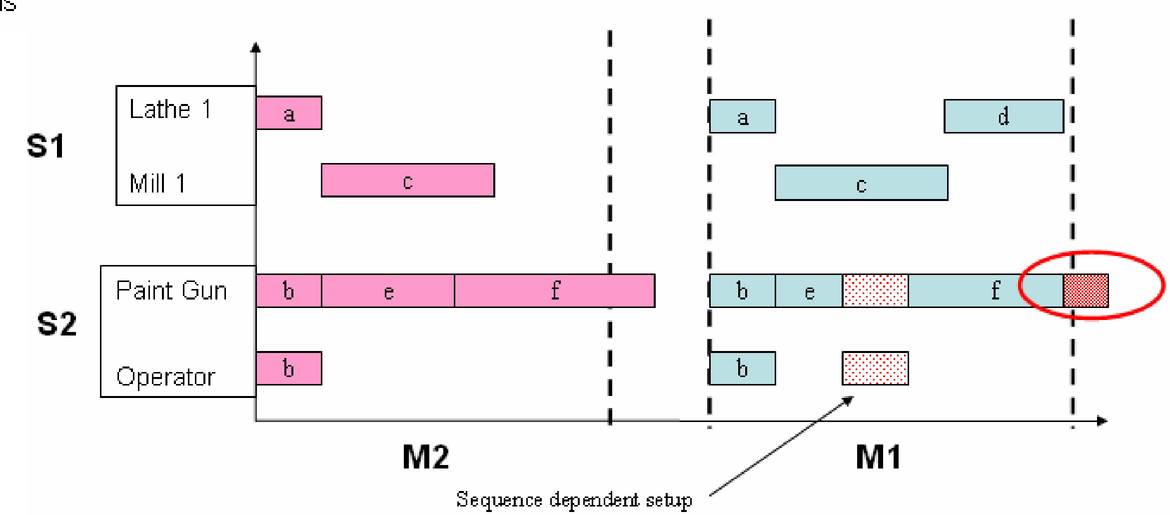
* *David W. He & Andrew Kusiak, Design of Assembly Systems for Modular Products, IEEE Transactions, Vol 13, No 5, Oct 1997*
** *Balancing & Sequencing of Assembly Lines, 2nd edition, Armin Scholl, 1999*

Mixed Model Lines cont…



- Mixed Model Balancing
  - Determine where the tasks need to be performed (station assignment) so that station loads are balanced across models

- Mixed Model Sequencing
  - Determine ***Model Mix*** - selecting sequence of models to produce on the line
  - Determine ***Launch Interval*** - selecting the time interval between successive launches of units



Balancing with Models & options

- Models vs. Options in mixed model balancing
  - Product : Toyota Corolla
  - Models : CE, S, LE, XRS
  - Options : Additive (Anti-lock Brake System, MP3 player, etc.)
  - Options: Mutually Exclusive (CD vs FM stereo)
- Different approaches to include Models & Options in Balancing
  - Weighted average method (peak model, peak option)
  - Weighted average method (peak model, avg option)
  - Peak model method

Task Times

- One time for each task performed at each model.
  - Large data sets, complexity and lack of association to mult. Models as well as precedence
- One time for a task shared for models
  - Different tasks when time is different between models
  - Different time to same task when time is different between models.

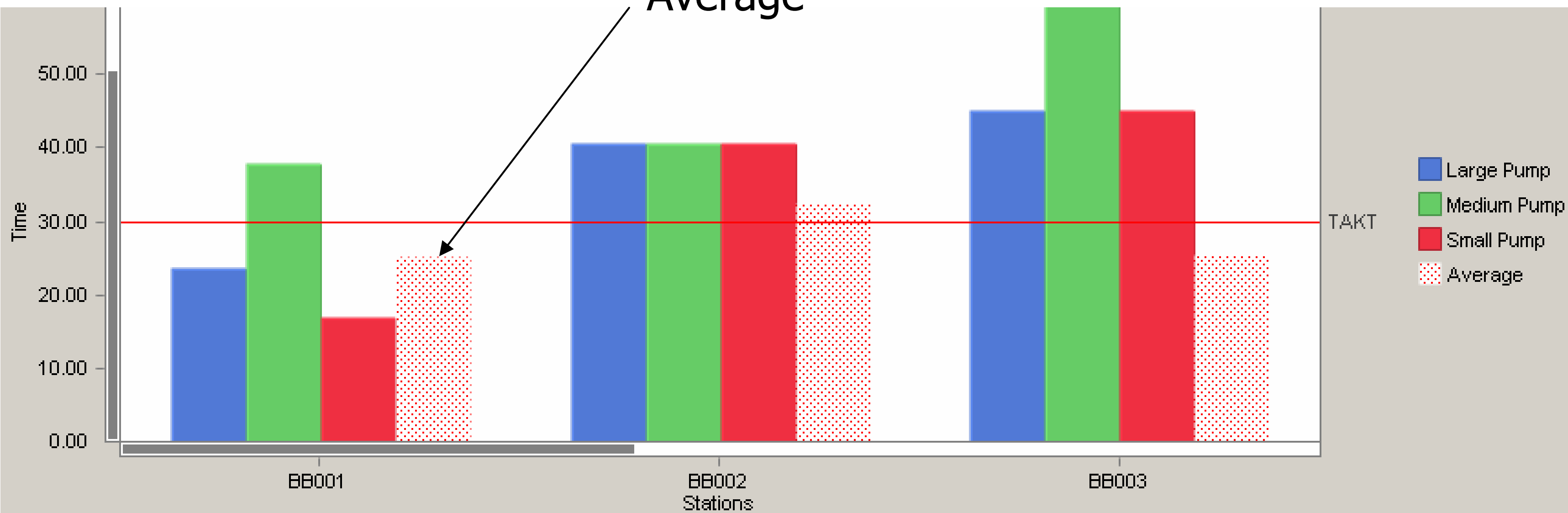
Weighted average method

- Compute composite process times
  - Process times weighted using Model & Option demand percentages
- Line Balanced for weighted time at each station
- Depends on station times being balanced across models

Task	Standard Time	Large Pump (30 %)	Medium Pump (30%)	Small Pump (40%)	Composite Time (Weighted Time)
PP01S-1	12	3.60	0.00	4.80	8.40
PP01S-2	14	4.20	0.00	0.00	4.20
PP01S-3	16	4.80	4.80	6.40	16.00
PP01S-4	18	0.00	5.40	0.00	5.40
PP01S-5	18	0.00	0.00	7.20	7.20

Weighted Average Method

Balanced for weighted Average



Select Station: BB001 Station Time: 25.22 Time Unit: Seconds

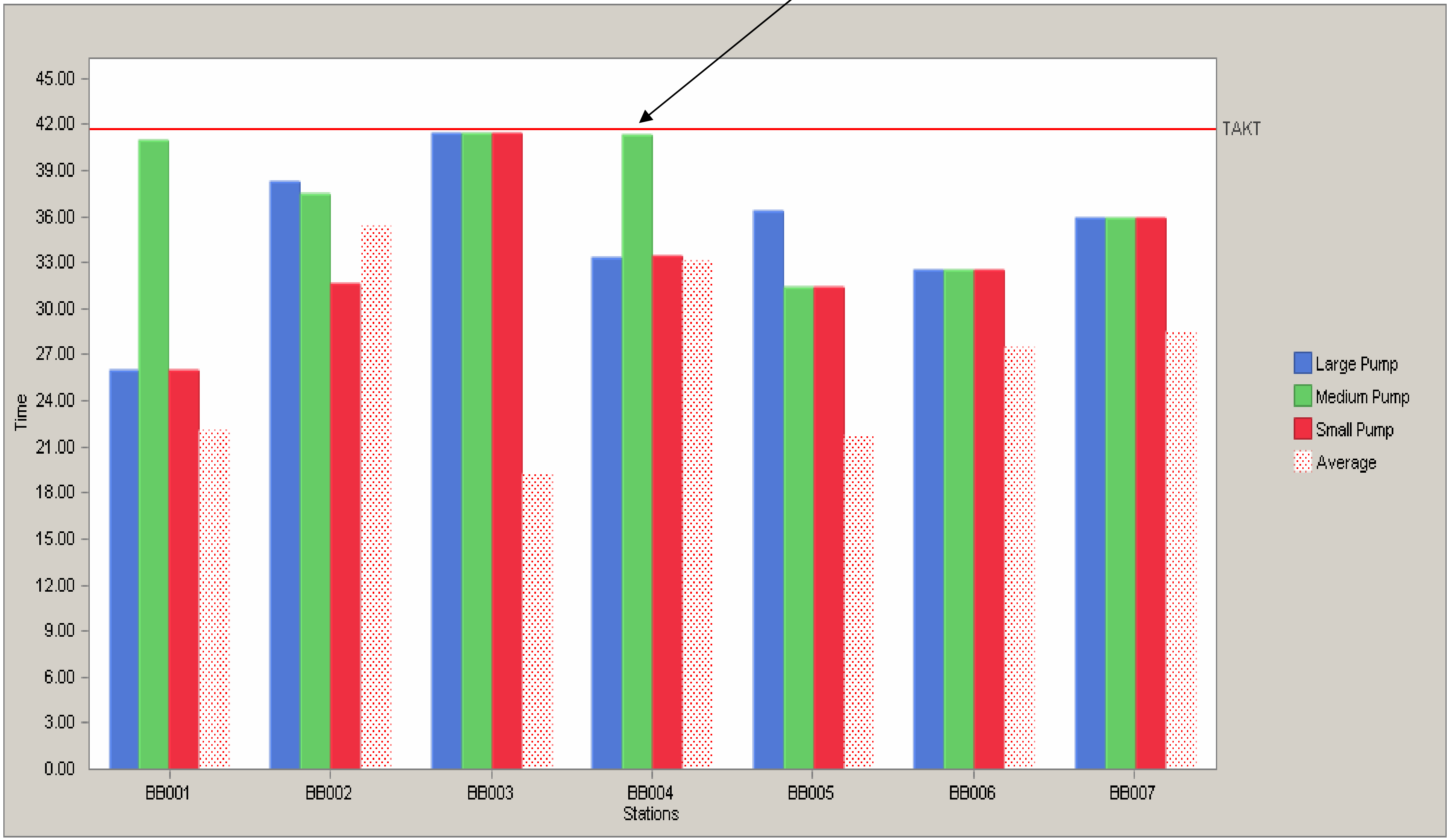
	ID	Description	Net Time	Wt. Time	Violations	Models	Options	Resource	LineSic
1	40S-010	Pull tie wrap tight and trim.	15.00	4.50		Medium Pump			E
2	40S-002	Press U-Cup into housing.	6.60	1.98	M	Large Pump		1124	E
3	40S-001	Lube U-Cup.	9.00	9.00	P R			FIXTURES1,L-OIL	E
4	40S-003	Lubricate and press grommet into housing.	8.00	8.00	M			LATHE1	E
5	40S-004	Install motor into housing.	5.80	1.74	R	Medium Pump		BENDER144	E

Peak model method

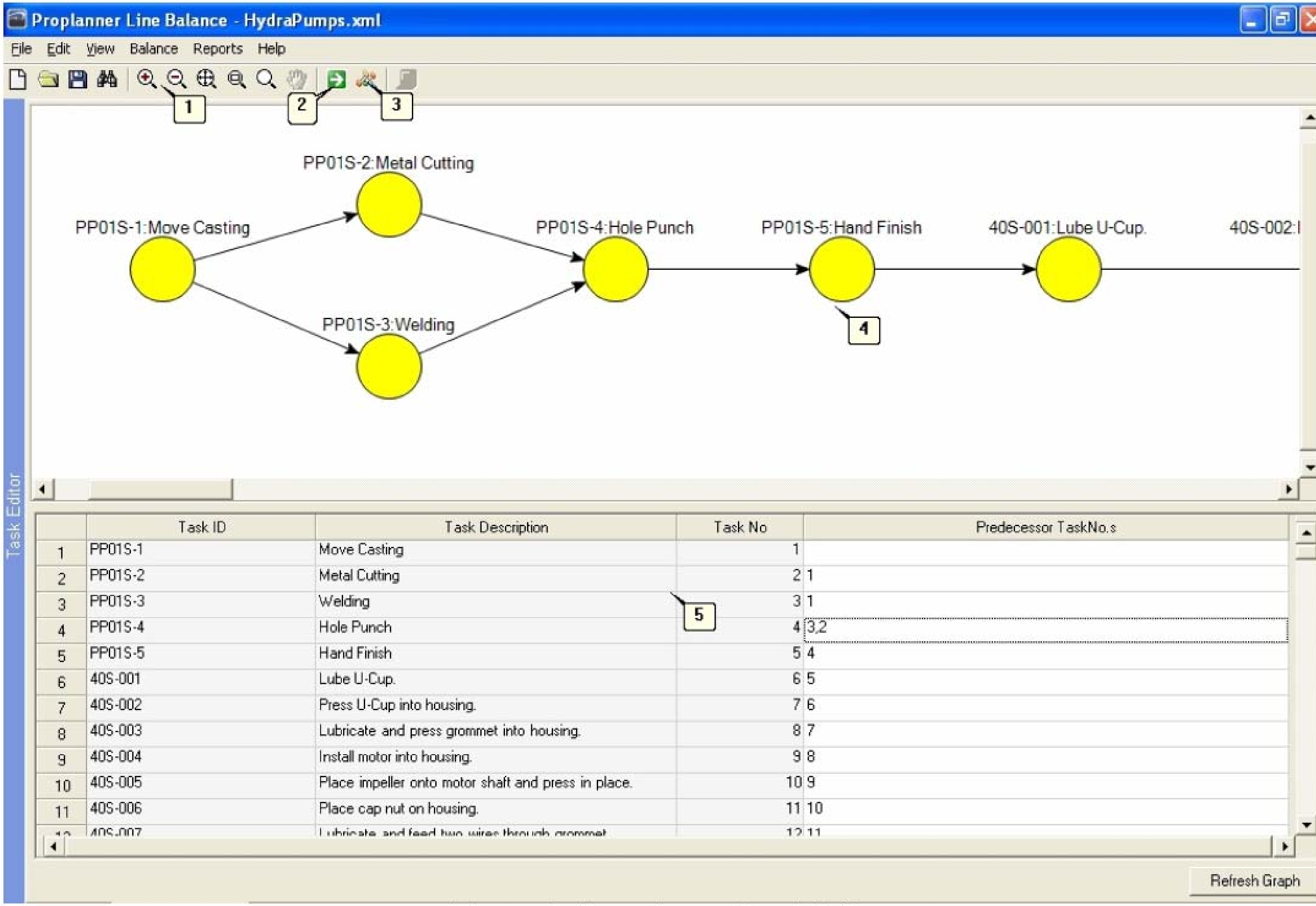
- Stations balanced for true model time rather than average time.
- More conservative approach.
- Line could be under utilized if spread between max & min model times is high.
- Option times can be a weighted average or the additive options (Added) and the exclusive options (Longest).
- COMSOAL modification
  - Maintain an array of model times for each station
  - In Step 4 (Time Feasibility), check for worst model time at the station

Peak model method cont…

Balanced for worst model time

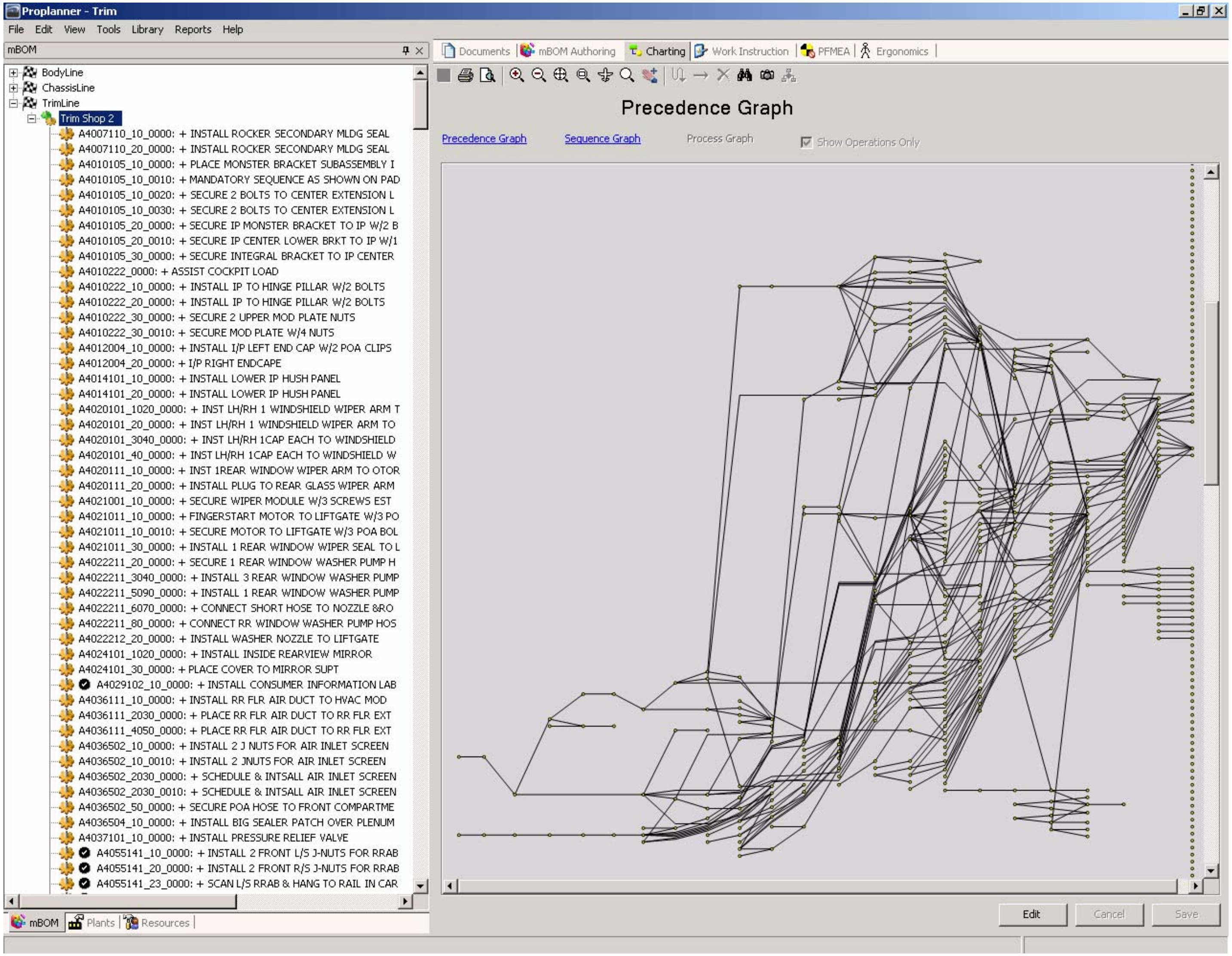


Precedence

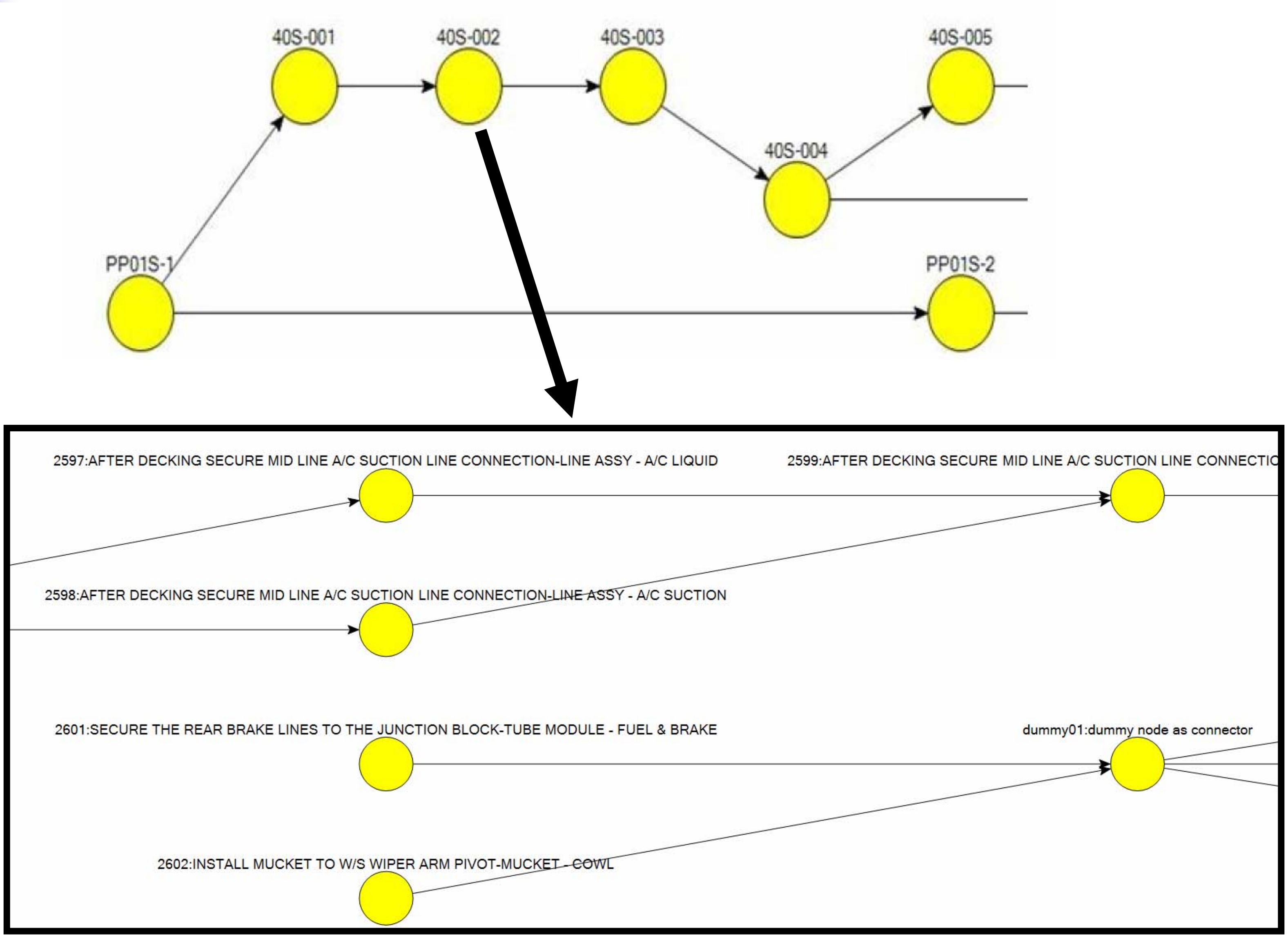


	Task ID	Task Description	Task No	Predecessor TaskNo.s
1	PP01S-1	Move Casting	1	
2	PP01S-2	Metal Cutting	2	1
3	PP01S-3	Welding	3	1
4	PP01S-4	Hole Punch	4	3,2
5	PP01S-5	Hand Finish	5	4
6	40S-001	Lube U-Cup.	6	5
7	40S-002	Press U-Cup into housing.	7	6
8	40S-003	Lubricate and press grommet into housing.	8	7
9	40S-004	Install motor into housing.	9	8
10	40S-005	Place impeller onto motor shaft and press in place.	10	9
11	40S-006	Place cap nut on housing.	11	10
12	40S-007	Lubricate and feed two wires through grommet	12	11

Automotive Precedence



Hierarchical Precedence

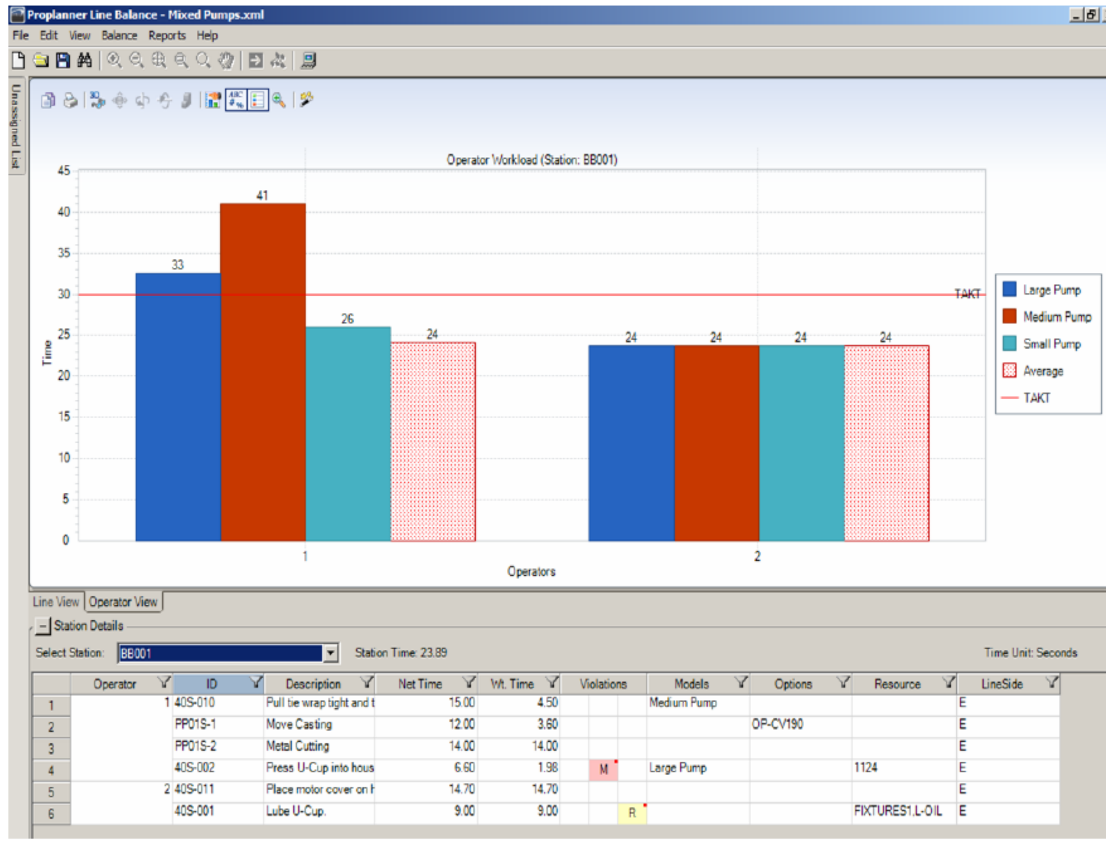


Operator/Station constraints

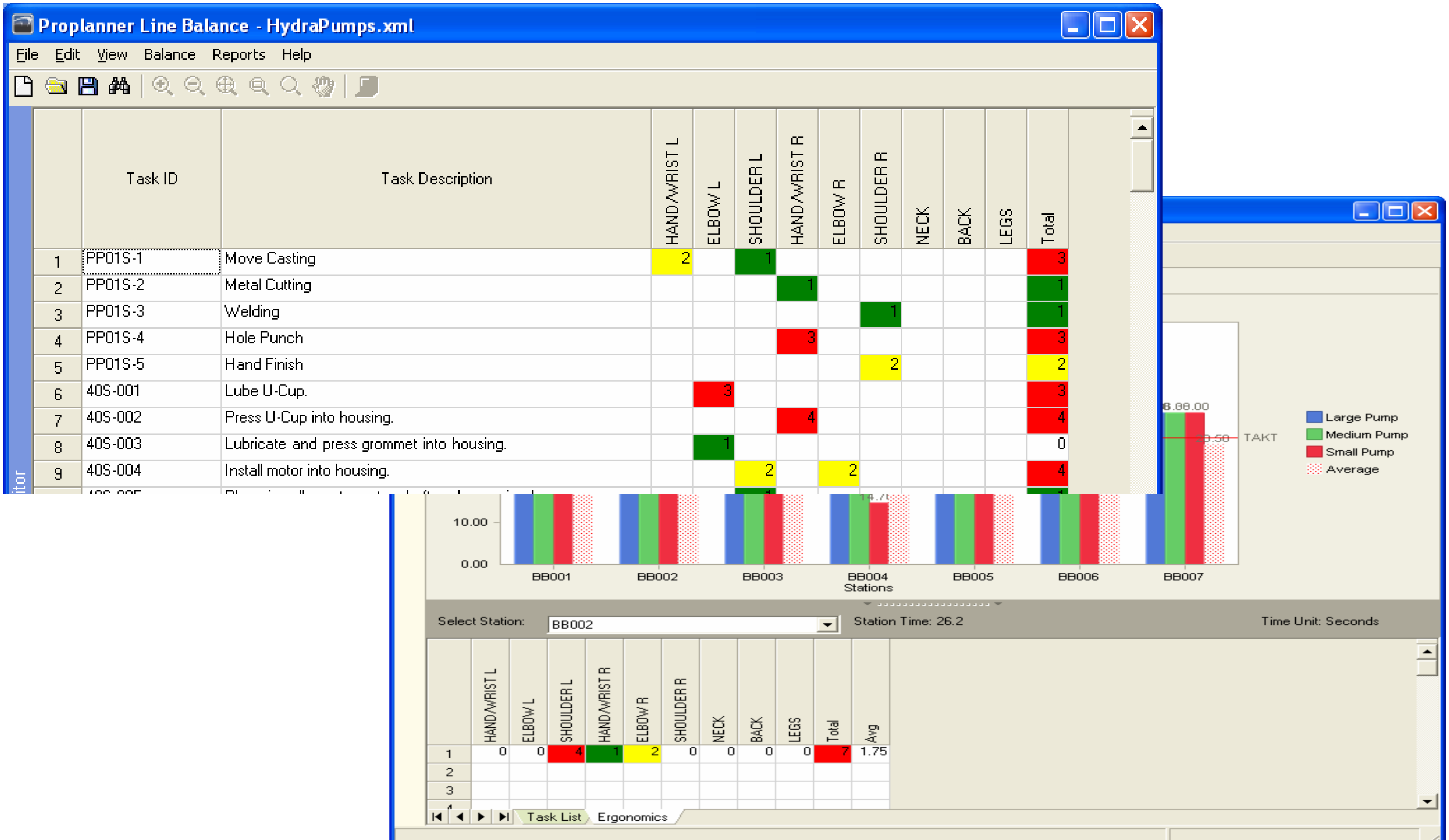
- Multiple operators per station
  - Available time at station factored by number of operators present at station
- Floating operators
  - Usually modeled as efficiency% on the operator
  - Available Operator time factored by efficiency%
    - For example, a operator moving between 2 stations could be given an efficiency of 60% in the first station, and 40% on the next station.
- Operator delay/idle time within stations
  - Caused by precedence between tasks assigned to station
- Ergonomic constraints
  - Cannot overload a single operator with a specific kind of task
- Room for Line-Side Materials

Multiple Operators Per Station

- Not same as multiple stations
- Is precedence between operators considered?

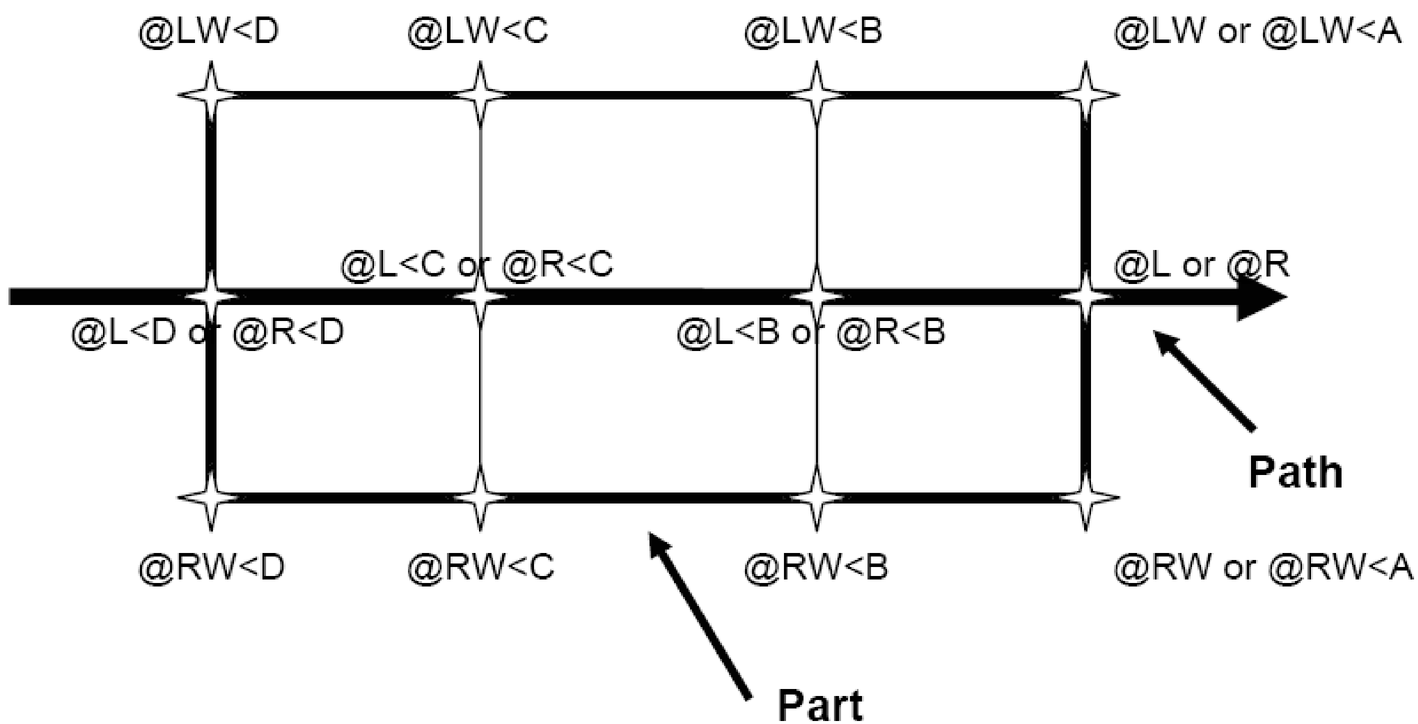


Ergonomic Constraints



Workzone Constraints

- Part Zones (R, L, Under, Above)
- Detailed Part Zones (downstream)



Balance Efficiency

Report Viewer

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Station Balance Report

Scenario: SampleHydraPumps-Mixed.xml **Takt Time:** 47 Sec. **Total Line Time:** 188.41 Sec.

	Maximum	Minimum	Average
Station Time (Sec.)	46.44	12.5	37.682
Idle Time (Sec.)	34.5	0.56	9.318
Utilization (%)	98.80	26.60	80.20

Station ID: BB001 (L)

Station Idle Time: 0.56 (Sec.)

Station Time: 46.44 (Sec.)

Station Utilization: 98.80 %

Model Details:

ID	Time (Sec.)	Utilization %
Large Pump	57.8	123.00
Medium Pump	72	153.00
Small Pump	51.2	109.00

Station ID: BB002 (L)

Station Idle Time: 0.9 (Sec.)

Station Time: 46.1 (Sec.)

Station Utilization: 98.10 %

Model Details:

ID	Time (Sec.)	Utilization %
Large Pump	51.5	110.00
Medium Pump	69.5	148.00
Small Pump	69.5	148.00

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Balance Implementation

Report Viewer

proplanner

Station Summary Report

Scenario: Mixed Pumps.xml
Takt Time: 47 Sec.

Station ID: BB001 (L)

Processes					Required Resources		
Operator	ID	Description	Net Time (Sec.)	Line Side	ID	Name	Quantity
1	PP01S-1	Move Casting	12.0000	E			
1	40S-010	Pull tie wrap tight and trim.	15.0000	E			
1	40S-001	Lube U-Cup.	9.0000	E	FIXTURES1		1
					L-OIL		1
1	40S-004	Install motor into housing.	5.8000	E	BENDER144		1
2	PP01S-2	Metal Cutting	14.0000	E			
2	40S-011	Place motor cover on housing and sonic weld.	14.7000	E			
2	40S-002	Press U-Cup into housing.	6.6000	E	1124		1
2	40S-003	Lubricate and press grommet into housing.	8.0000	E	LATHE1		1

Total: 42.5500 Sec.

Station ID: BB002 (L)

Processes					Required Resources		
Operator	ID	Description	Net Time (Sec.)	Line Side	ID	Name	Quantity
1	PP01S-3	Welding	16.0000	E			
1	40S-005	Place impeller onto motor shaft and press in place.	7.5000	E	LATHE2		1
1	PP01S-4	Hole Punch	18.0000	E			
1	40S-006	Place cap nut on housing.	3.5000	E	DR224		1

Total: 45.0000 Sec.

Station ID: BB003 (L)

Processes					Required Resources		
Operator	ID	Description	Net Time (Sec.)	Line Side	ID	Name	Quantity
1	PP01S-5	Hand Finish	18.0000	E			

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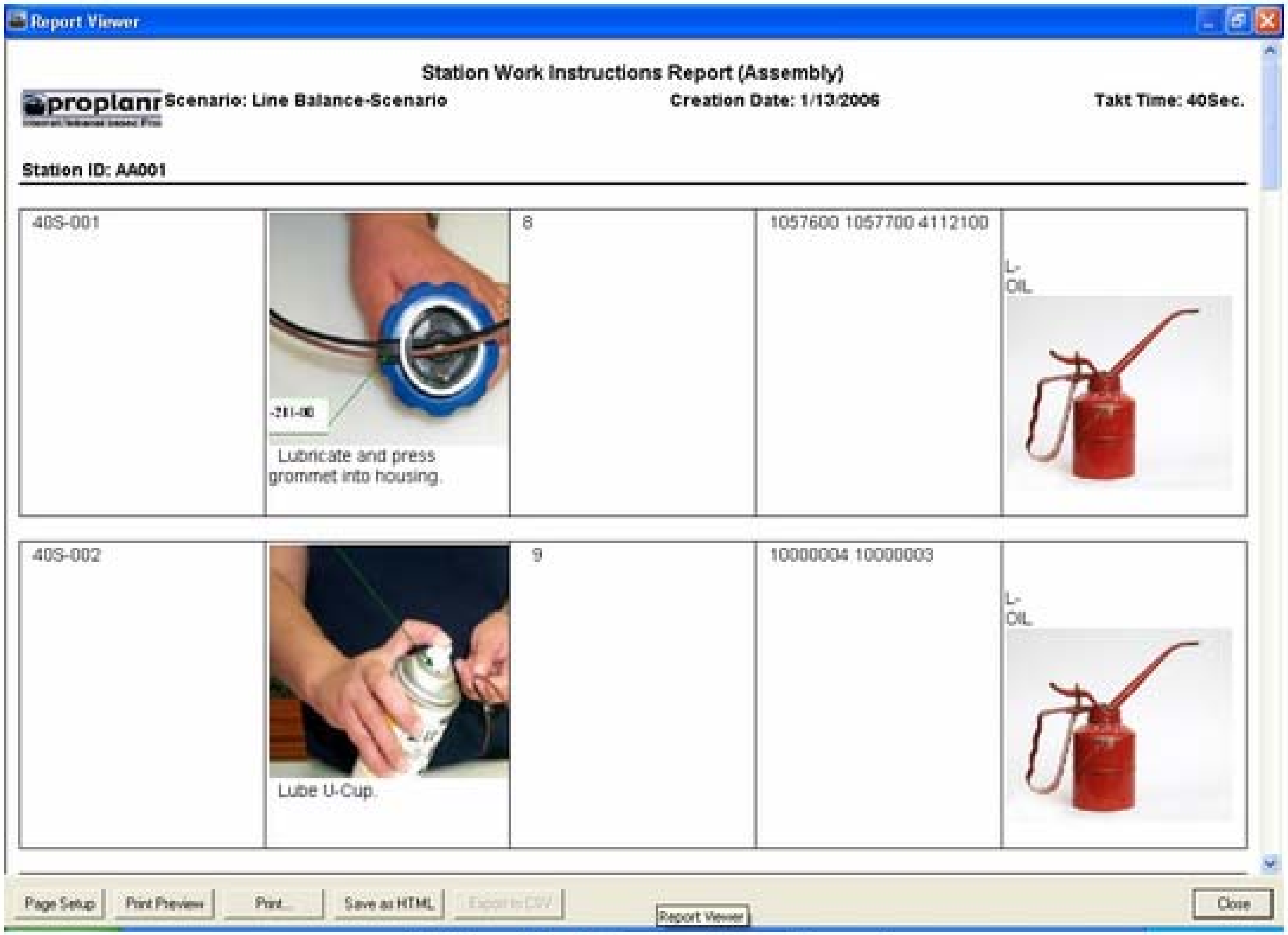
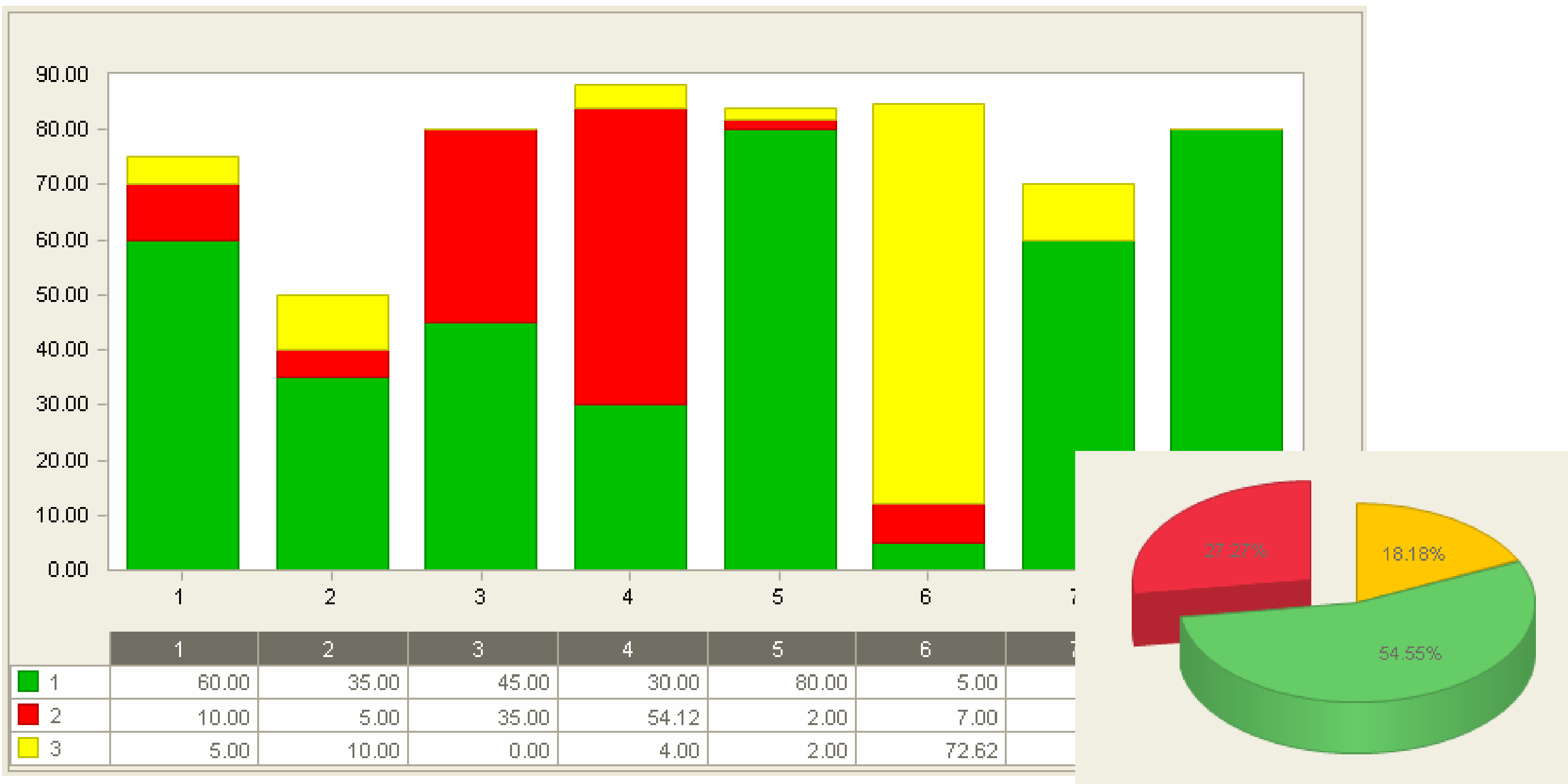
Work Instructions



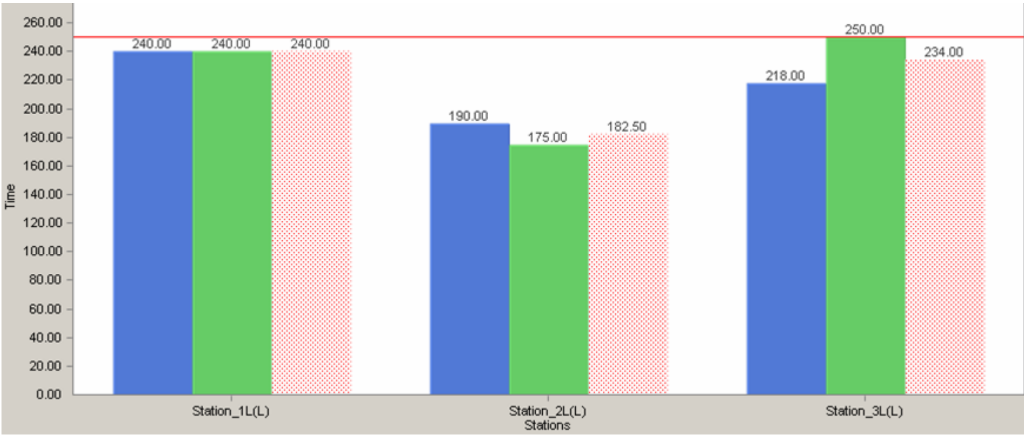
Lean Charting

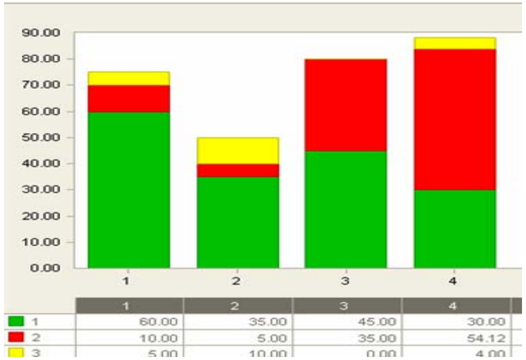
- LEAN charting during balancing could help in reducing Non-Value Added work at stations
- Analyzing operator walks (Non-Value Added) at bottle-neck stations could help in reducing overall cycle time

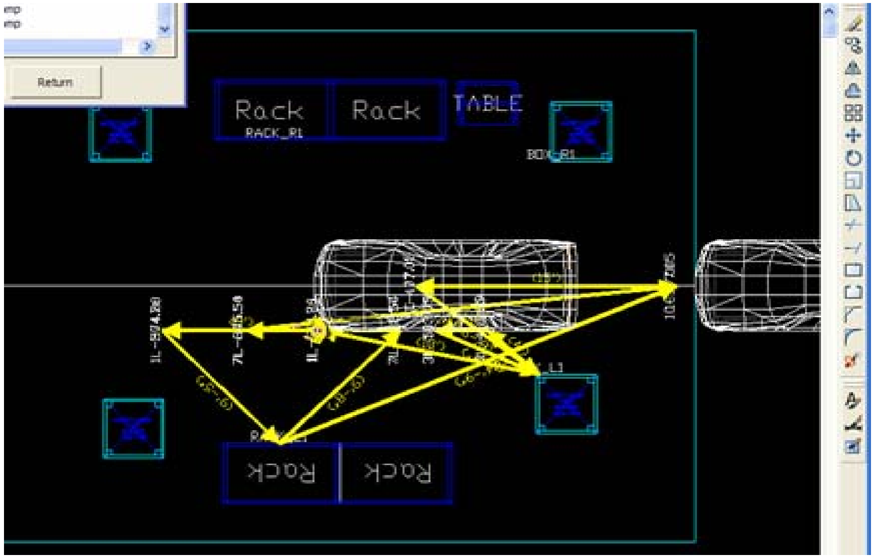


	1	2	3	4	5	6
1	60.00	35.00	45.00	30.00	80.00	5.00
2	10.00	5.00	35.00	54.12	2.00	7.00
3	5.00	10.00	0.00	4.00	2.00	72.62

Operator Walk Analysis



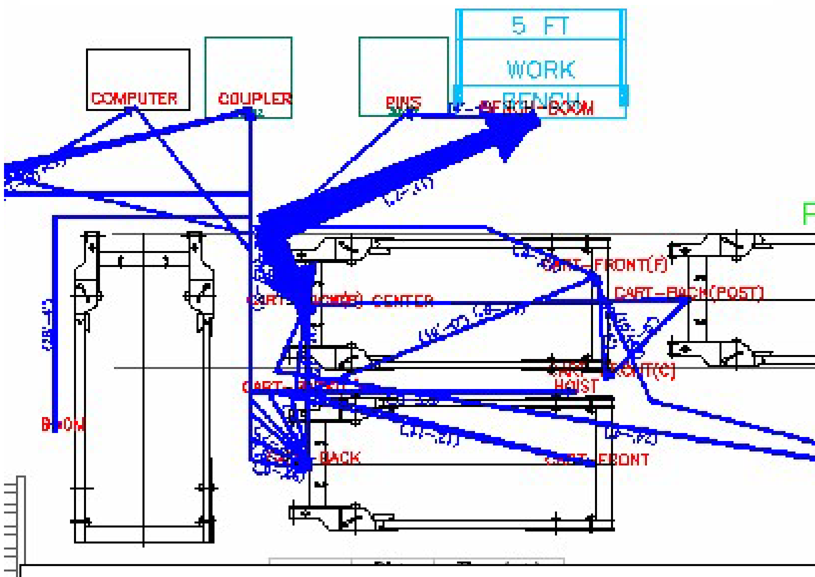




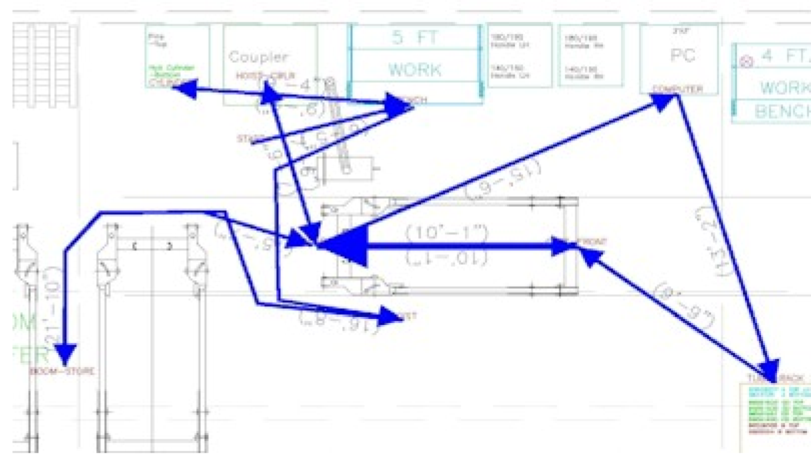
Operator Walk Analysis cont…

Case Study: Process Improvement at Skid-Loader Manufacturer

Before



After

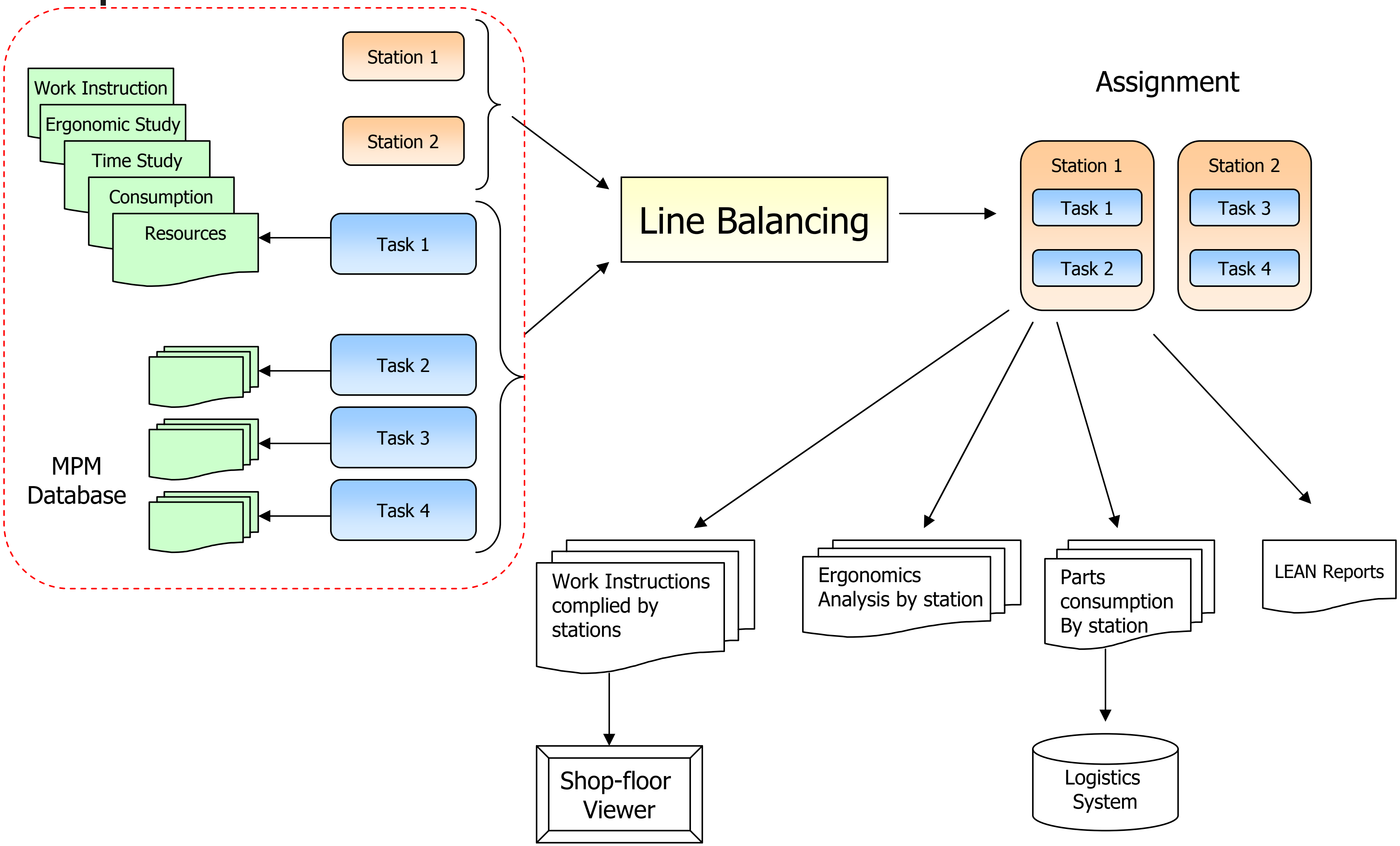


The engineers calculated that the walk-distance and time per unit was 551 feet and 3.5 minutes respectively. After the layout was changed the engineers calculated an estimated walk-distance and time of 166 feet and 1.1 minutes. The goal of the project was to cut down the existing 19 minute cycle time to 15 minutes per end unit assembled. This is a reduction of over 20%, and resulted in saving of $500 per unit assembled.

MPM & Line Balancing

- Manufacturing Process Management (MPM): Central repository & work bench for manufacturing data similar to PDM for design data
- Design tools such as Line Balancing could harness the relational data attached to process steps
  - Tasks have related data such as Time Studies, Ergonomic studies, Consumption data, Work Instructions, etc.
- Allows for frequent & better balancing
  - Reuse of process information
  - Easy access to process information
  - Automated workflow & reports
  - Availability of Sensitivity & Impact analysis tools
- PDM has reduced New Product Design times.
  - Manufacturing needs to adapt to frequent & faster design changes
  - Currently assembly line changes a major bottle neck in launch of new products

MPM & Line Balancing



References & Resources

- References

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  - Scholl, A. and C. Becker: A note on "An exact method for cost-oriented assembly line balancing". International Journal of Production Economics 97 (2005), pp. 343-352.
  - Boysen, N.; M. Fliedner and A. Scholl: A classification for assembly line balancing problems. Jenaer Schriften zur Wirtschaftswissenschaft 12/2006.

- Resources
  - http://www.wiwi.uni-jena.de/Entscheidung/alb/ - Contains recent research papers & sample problem sets.
  - http://www.proplanner.com – Commercial product containing additional line balancing information & product info.

Questions ?

Proplanner
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