Maintenance Scheduling & Planning – Case Studies

Effective Use of Maintenance Resources

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Agenda

- **Background**
- **Case Study 1: Steel Company**

  Dofasco Inc., Hamilton, Ontario, Canada
- **Case Study 2: Military Aircraft Fleet**

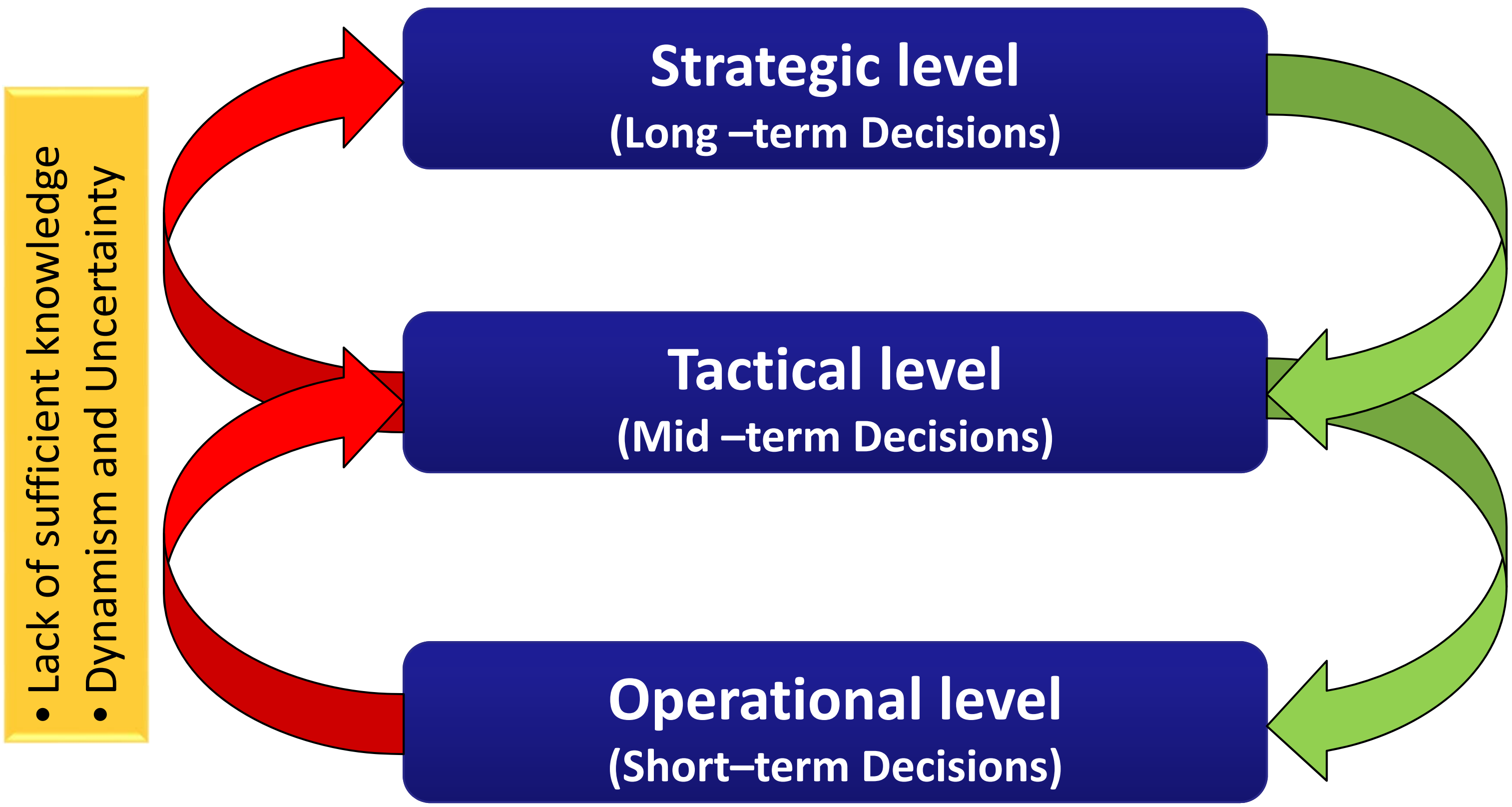
  Defense Science and Technology Laboratory (DSTL), U.K
- **Case Study 3: Electricity Transmission & Distribution**

  Hydro-One, Toronto, Canada
- **Case Study 4: Aircraft Maintenance Routing**

  Bombardier Aerospace, Canada

Background

Decision Levels



Background

Maintenance Tasks Scheduling Problem

- Is defined as scheduling of preventive/corrective maintenance jobs in a right time on a right equipment considering the available resources such as skilled workforce, tools, spare parts and space.

- Is a challenging issue in many industries with high variety of equipment and production such as steel company, airplane and automobile manufacturing, mining, electricity transmission, airlines, urban transportation, etc.

- **Job-shop Scheduling**: determining the sequence in which the maintenance work orders should be executed in a maintenance line at a service centre. Maintenance line refers to a physical slot/bay having required tools and skilled technicians.

Background

Requirements

- **Resources**
  - Workforce
  - Space
  - Spare parts
  - Tools
- **Objectives**
  - Workforce costs minimization
  - Asset **availability** maximization without additional capital investment
  - **Turnaround** minimization
  - **Open Capacity** (overage & underage) minimization
  - **Spare part** provisioning
- **Constraints**
  - Resources
  - Planning horizon
  - Multi-skilled workforce
  - Precedence relations
  - Job preemption
  - Transportation time/cost
- **Features**
  - Single/multi-shift scheduling
  - Static/dynamic scheduling
  - Offline/Online scheduling
  - Centralized/decentralized scheduling
- **MTC Task Characteristics**
  - Submission date
  - Due date
  - Weight (priority)
  - Processing time (duration)

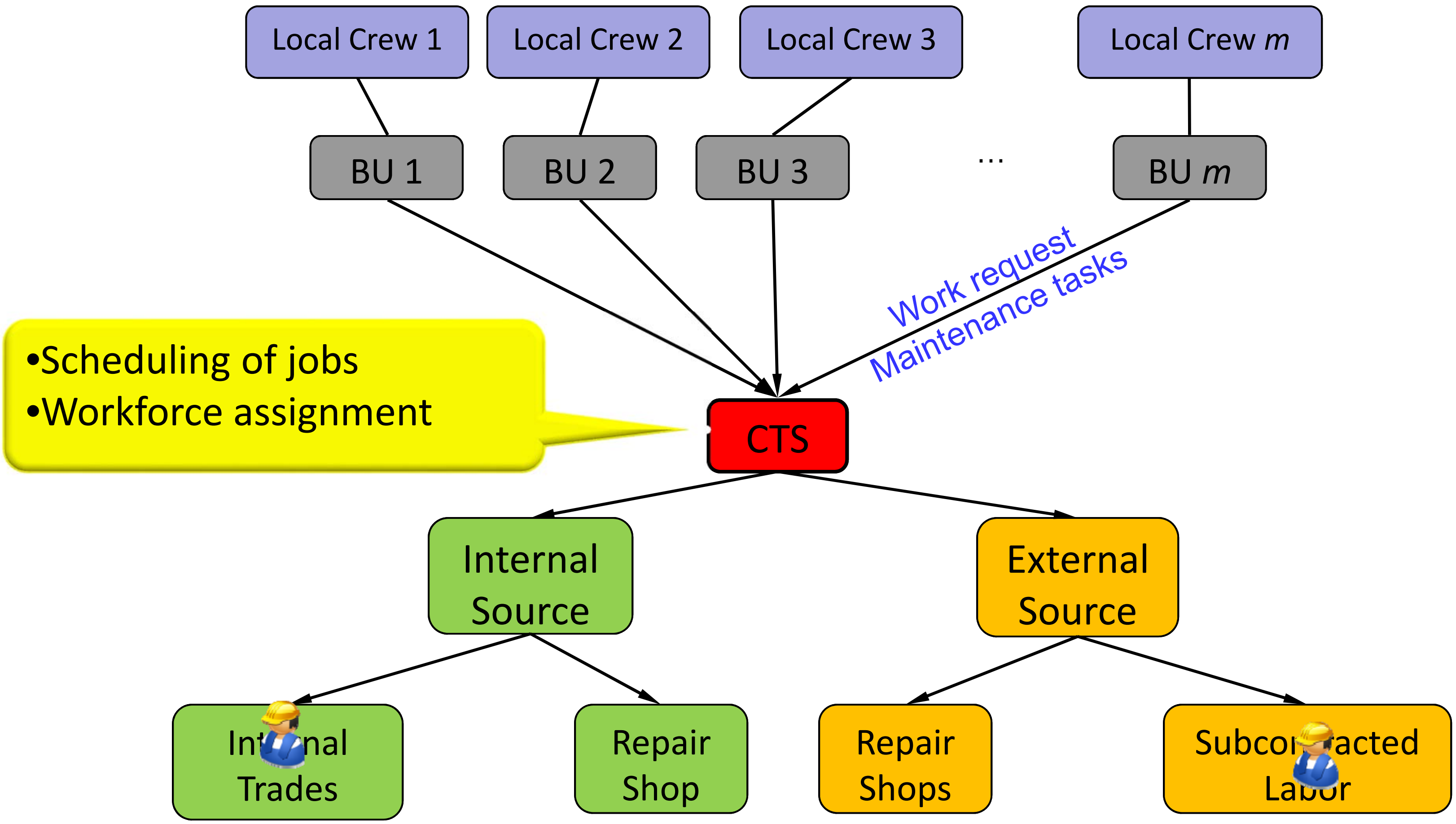
Case Study 1:

Steel Company

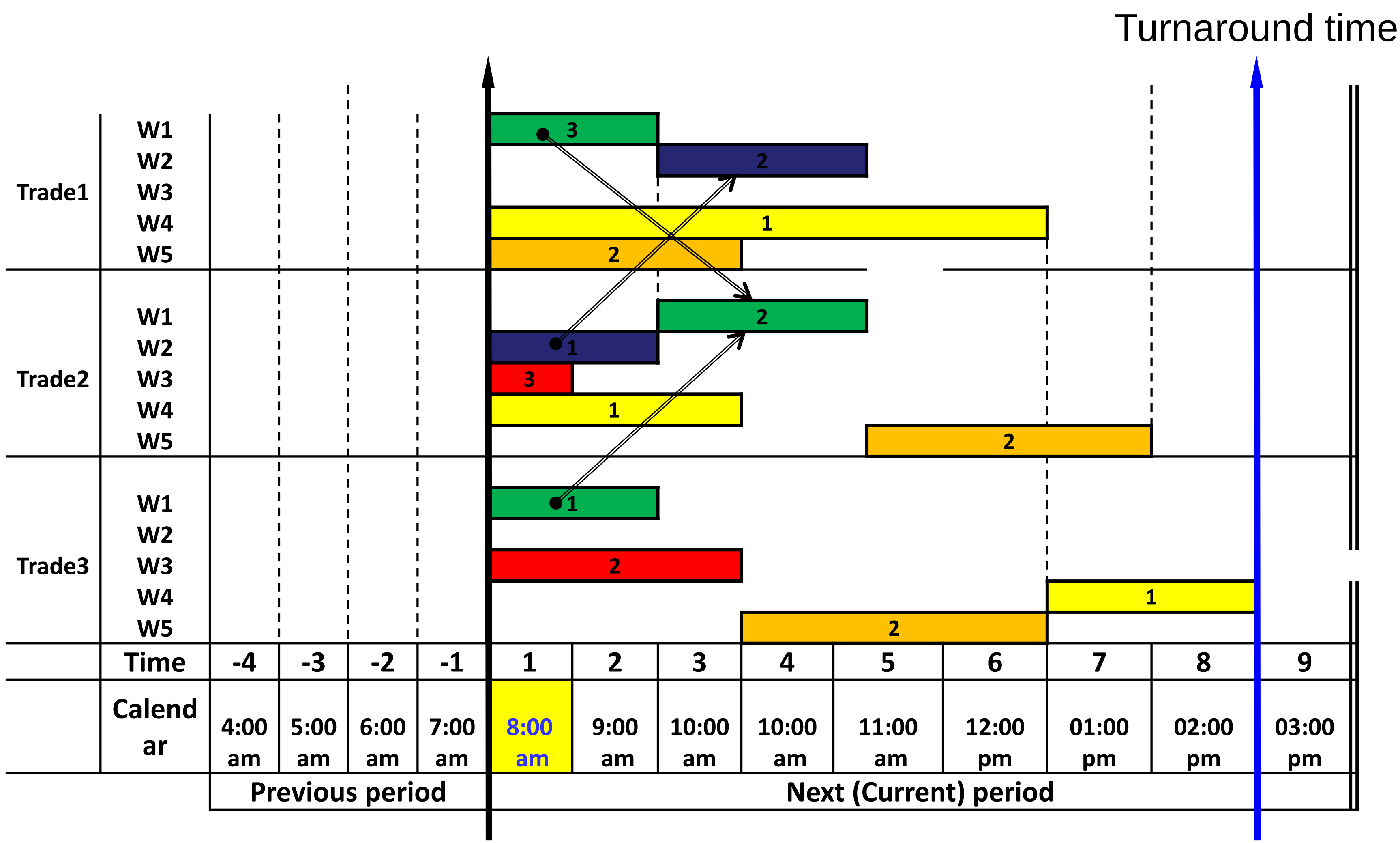
Safaei, N. Banjevic, D. Jardine, A.K.S., 2011, Bi-objective Workforce-constrained Maintenance Scheduling: A Case Study, ***Journal of Operational Research Society****,* Vol. 62, pp. 1005 –1018.

Safaei, N. Banjevic, D. Jardine, A.K.S., 2012, Multi-Threaded Simulated Annealing for a bi-objective Workforce-constrained Maintenance Scheduling Problem, ***International Journal of Production Research***, Vol. 50, No. 1, pp. 1-18.

Background
(Centralized Architecture)



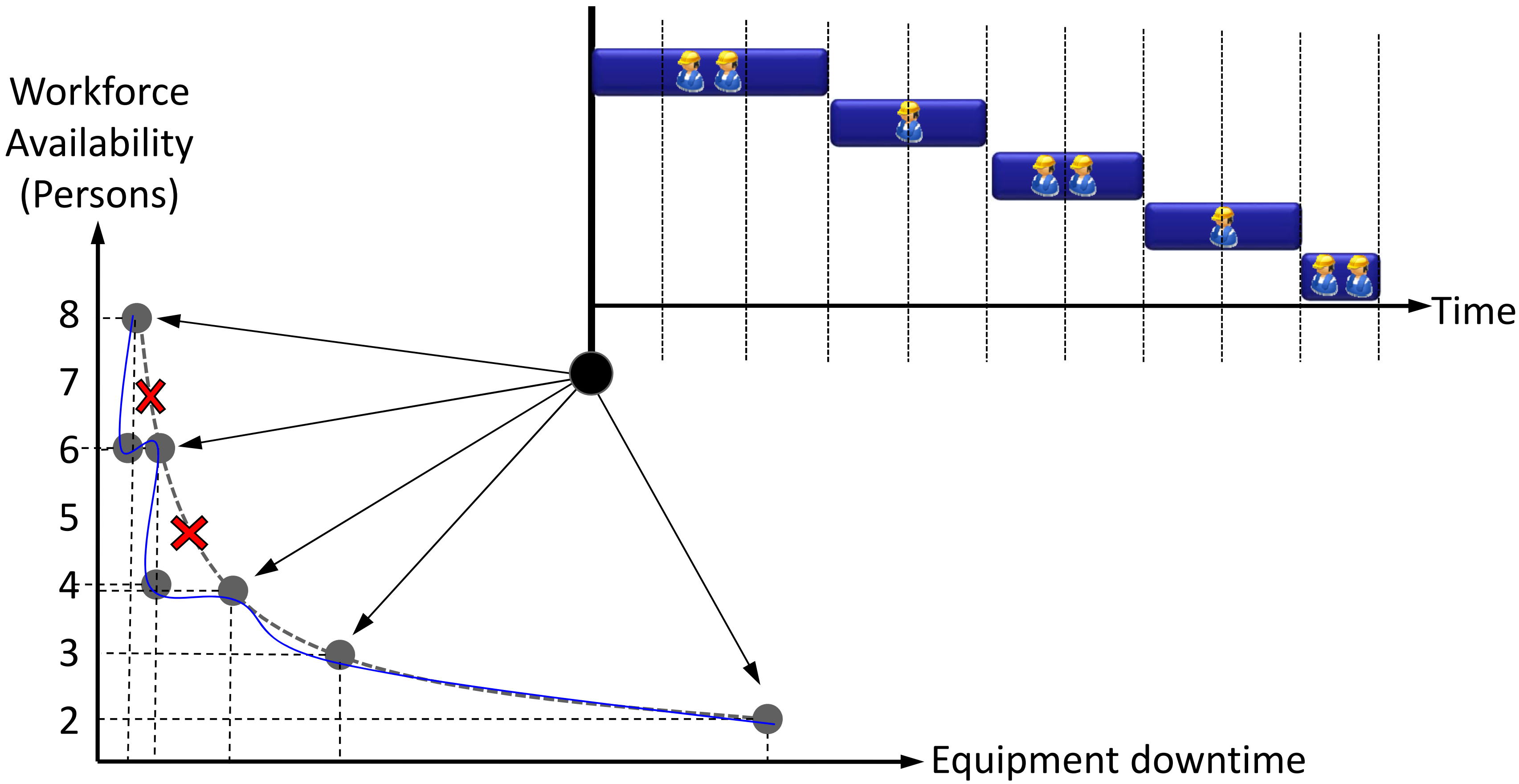
Typical Example - Daily scheduling



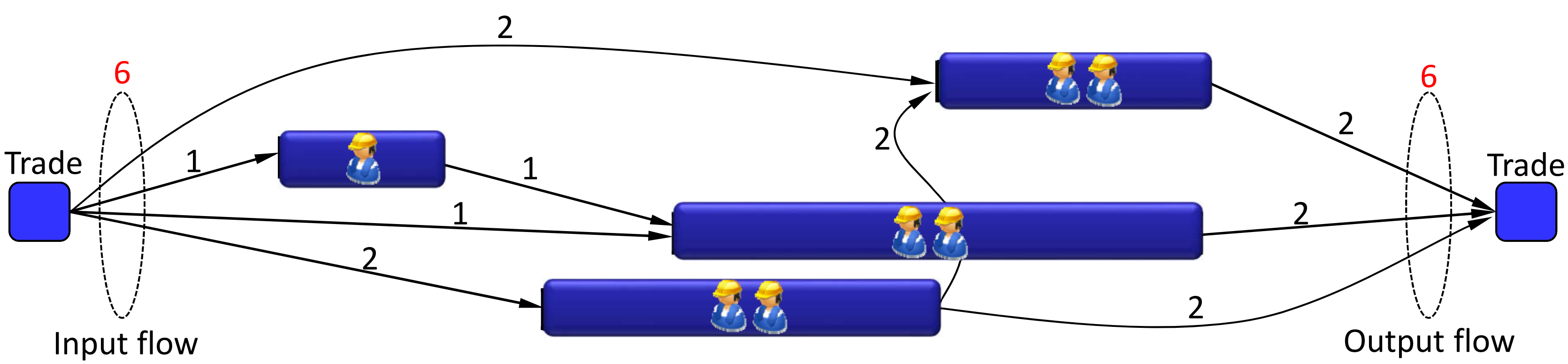
Remarks

- ***Manpower Limitation***: Maintenance jobs have to be scheduled when they occur. Consequently, manpower is a limiting factor.
- ***Equipment Availability***: is directly influenced by the schedule. The ability to be in time for all jobs will have direct impact on the availability of the assets.
- ***Work Prioritization***: work requests have different priorities depending upon the consequence of equipment downtime such as secondary failures, equipment criticality or customer order lateness.
- ***Dynamic Environment***: CTS encounters day-to-day requests that should be responded to in a timely manner.

Equipment Availability vs. Labor Resource Availability



Mobile Workforce Dispatching



Workforce dispatching can be formulated as a network structure in which the workforce is considered as flow, and jobs are nodes in the network

Problem Definition

Conflicting Objectives:

1. Minimizing the Equipment Downtime (BUs side)
2. Minimizing the *Workforce Costs/Requirements* (CTS side)

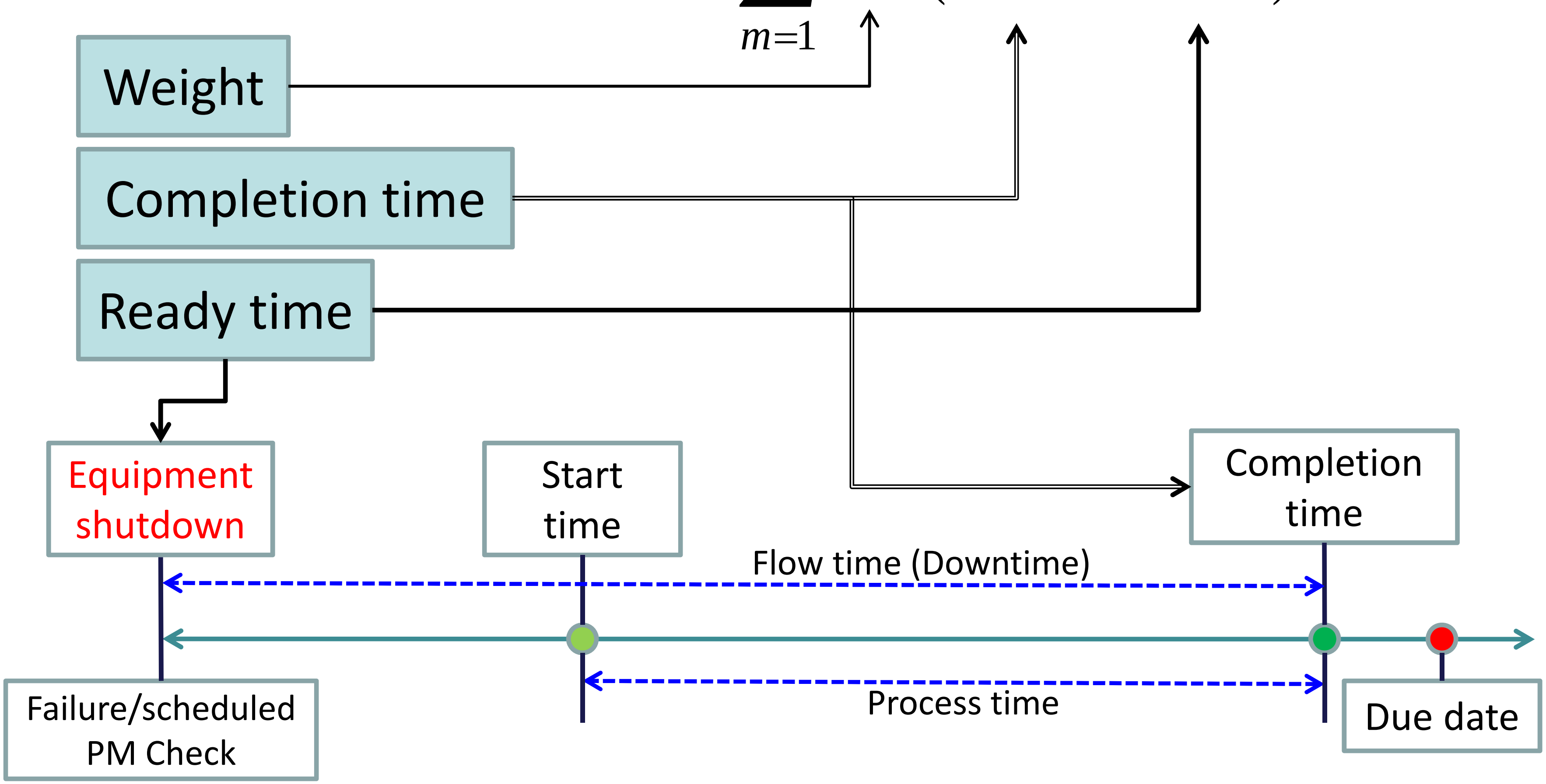
Constraints:

1. Internal and External labor resources
2. Precedence Relations between tasks
3. Max. equipment downtime

Total Weighted Flow Time

(A criterion to measure Asset Unavailability/Downtime)

$$TWFT = \sum_{m=1}^{M} w_m \left(CT_m - RT_m \right)$$



Maintenance Work Orders Prioritization

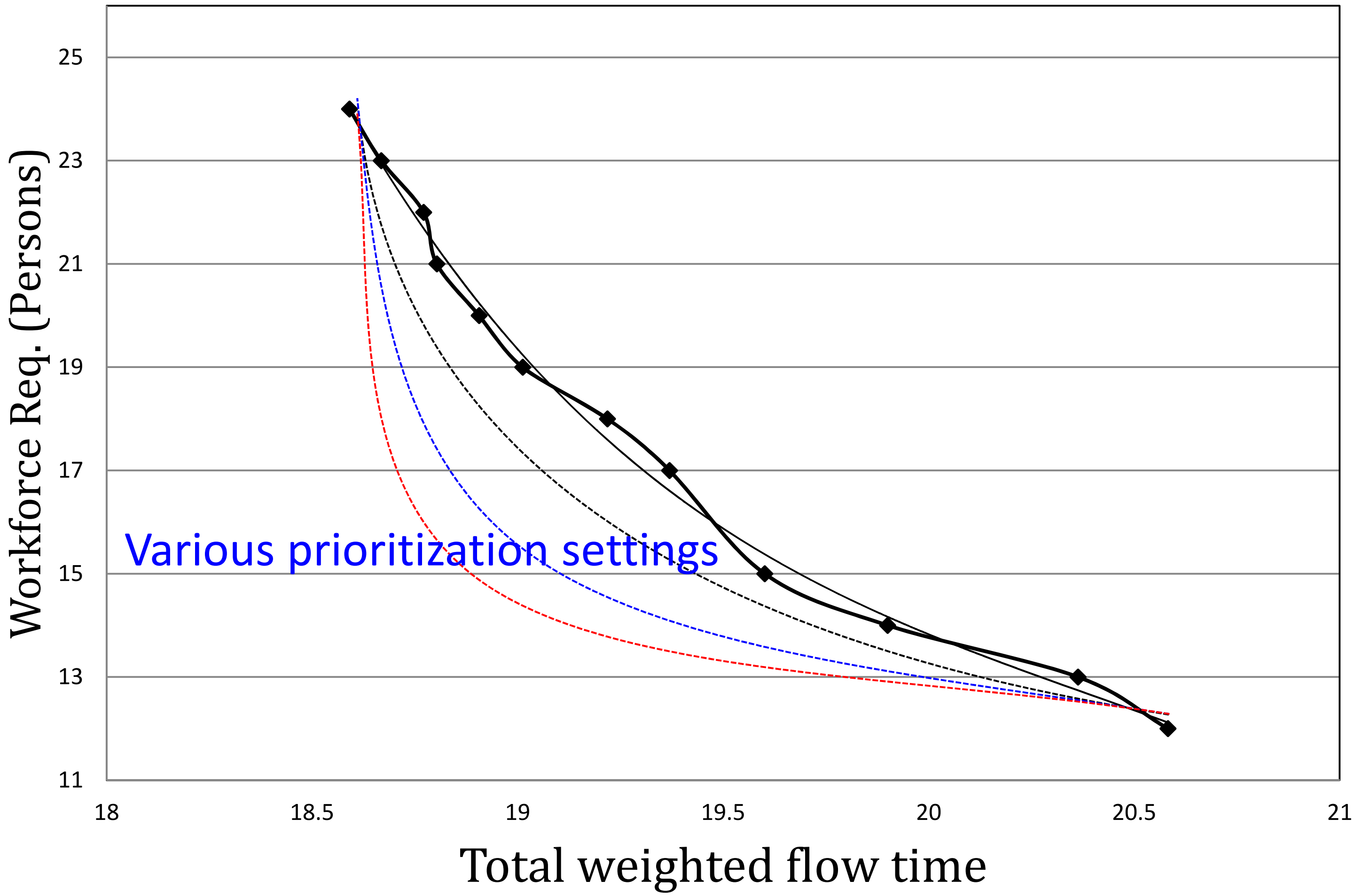
$$W_m = \frac{\alpha_m}{(Due\ Date\ - Ready\ Time)^{\beta_m}}$$

α_m = *Criticality* of equipment associated with work order *m* *(How much the equipment downtown contributes to the whole process?)*

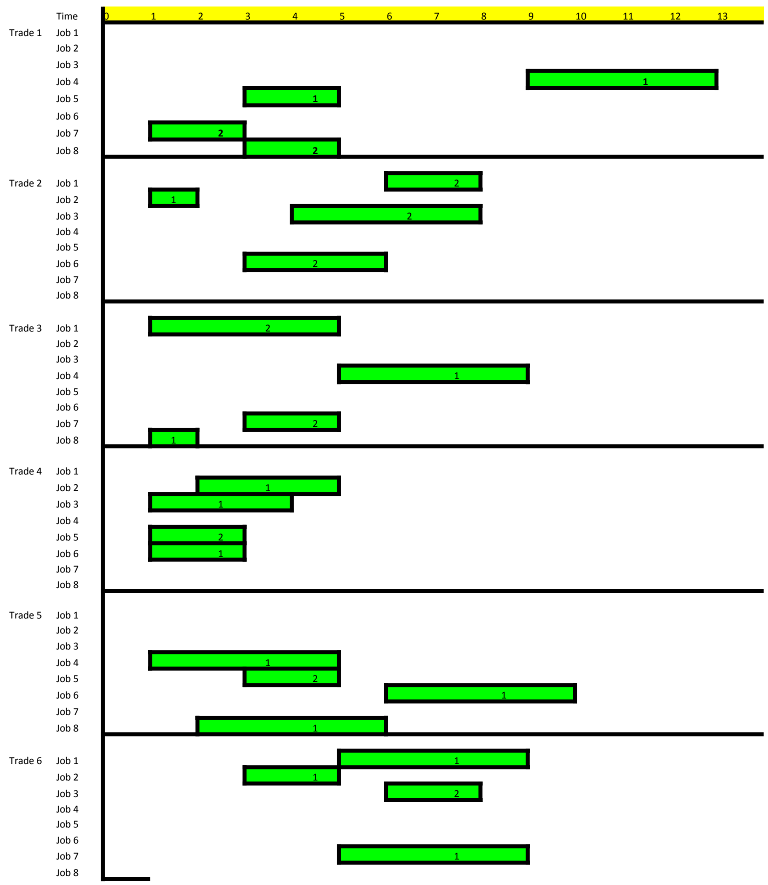
β_m = *Severity effect factor* of work order *m:*

- β>1: *Regular* failure with no cascading effect
- β<1: *Critical* failure with potential cascading effects

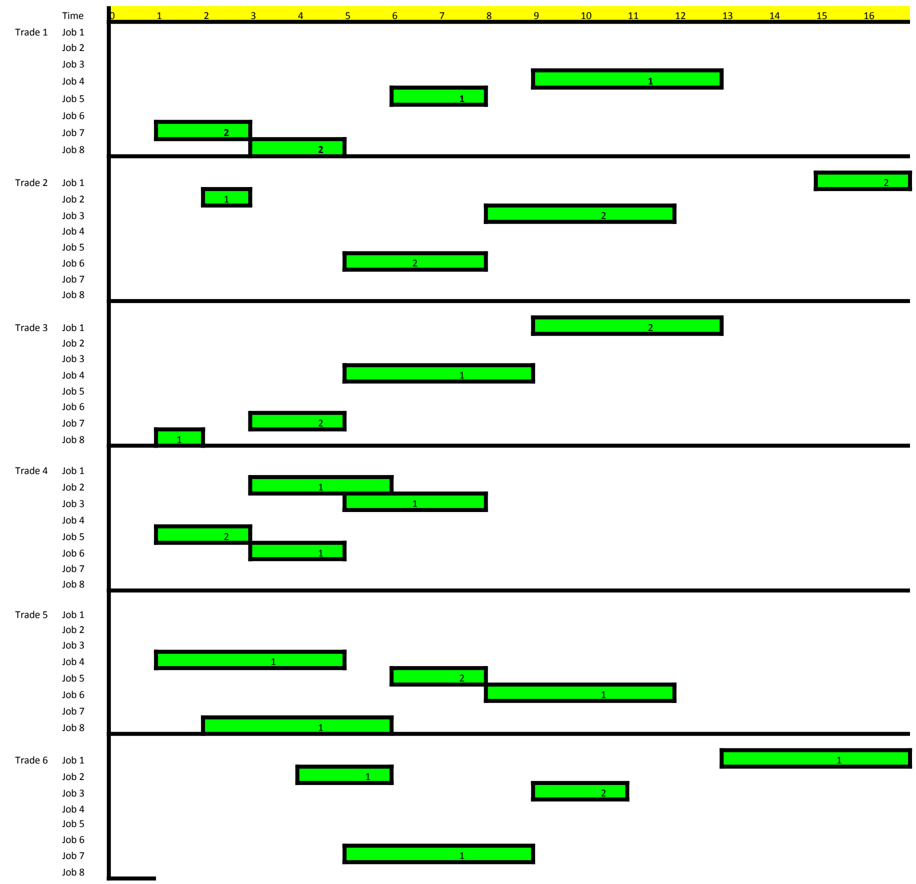
Trade-off between Conflict Objectives



Optimal Schedules – Extreme Scenarios

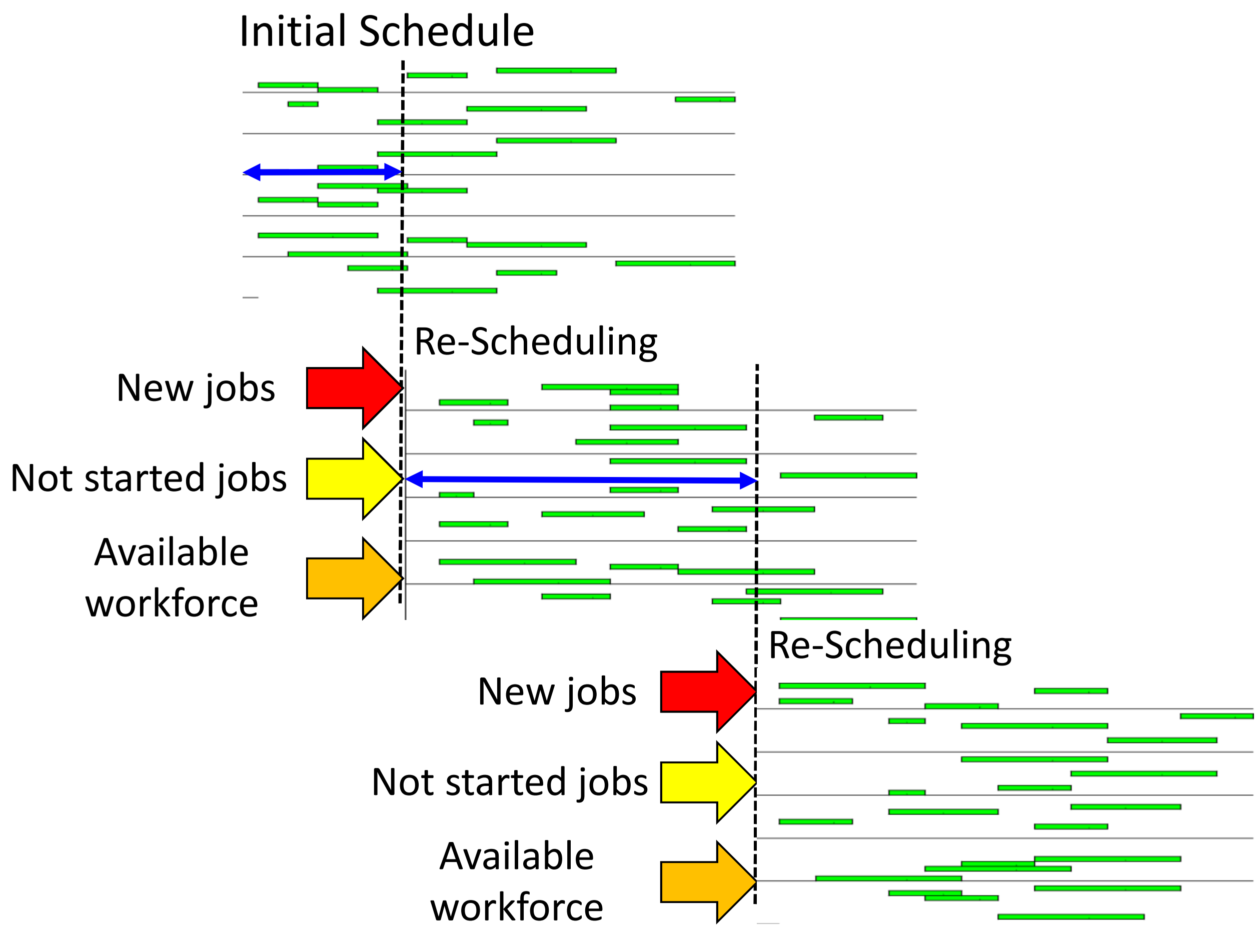


(Less downtime with more workforce)



(More downtime with less workforce)

Real-time Scheduling



Case Study 2:

Military Aircraft Fleet

Safaei, N., Banjevic, D. and Jardine, A.K.S. (2011), Workforce-constrained Maintenance Scheduling for Military Aircraft Fleet: A Case Study, ***Annals of Operations Research***, Vol. 186, No. 1, pp. 295-316.

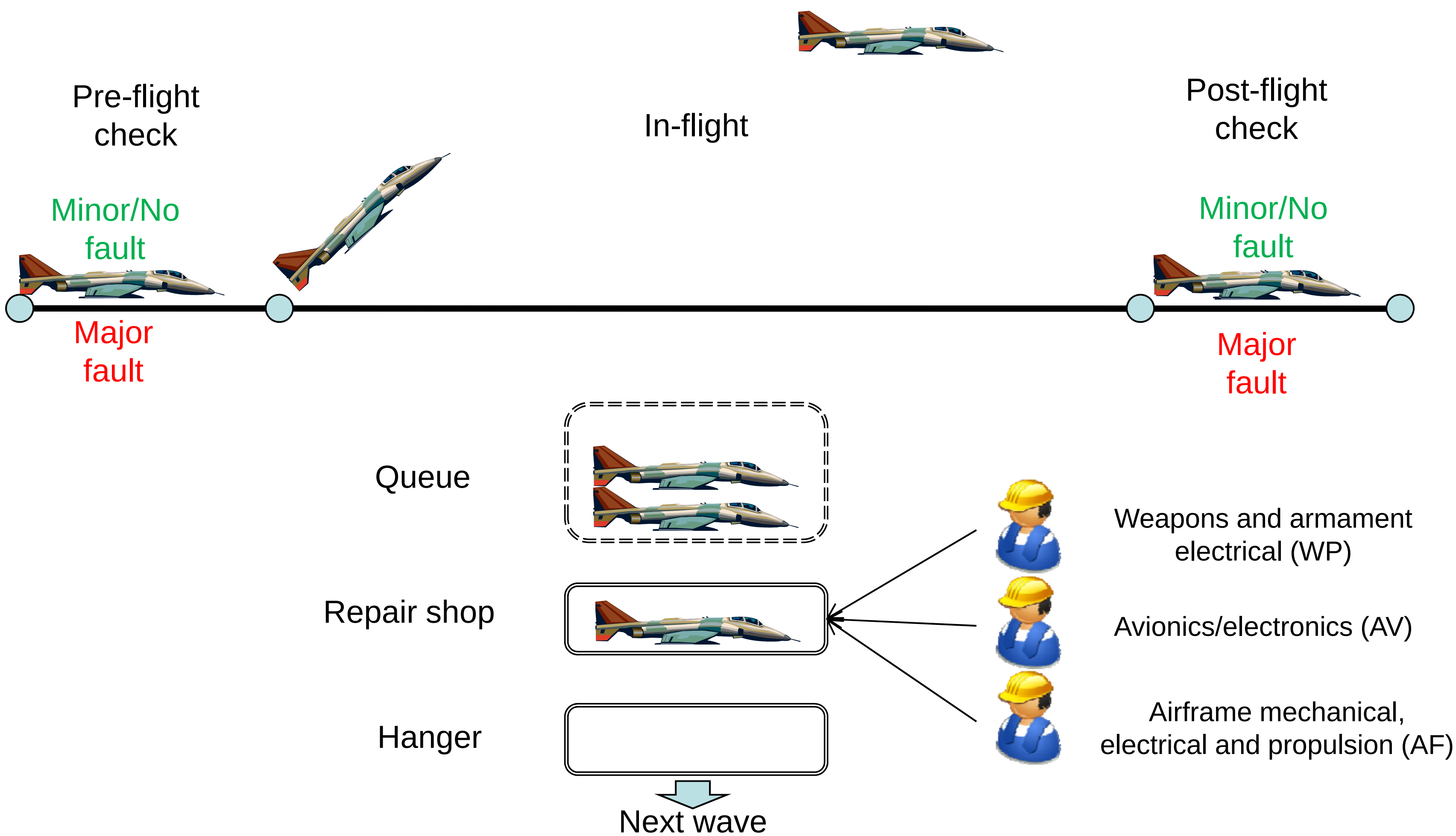
Background

1. The aircraft availability required to meet the flying program (scheduled waves or missions) is a challenging issue.
2. Each aircraft is inspected before flying (pre-flight check) and after landing (after-flight check) by fly technicians:
   - Major failures are referred to the repair shop, and
   - Minor faults are fixed whilst the aircraft stays on the flight line.
3. Scheduled preventive maintenance (PM) actions must be also accomplished in addition to the unplanned repair jobs.
4. Each repair job means a down aircraft $\Rightarrow$

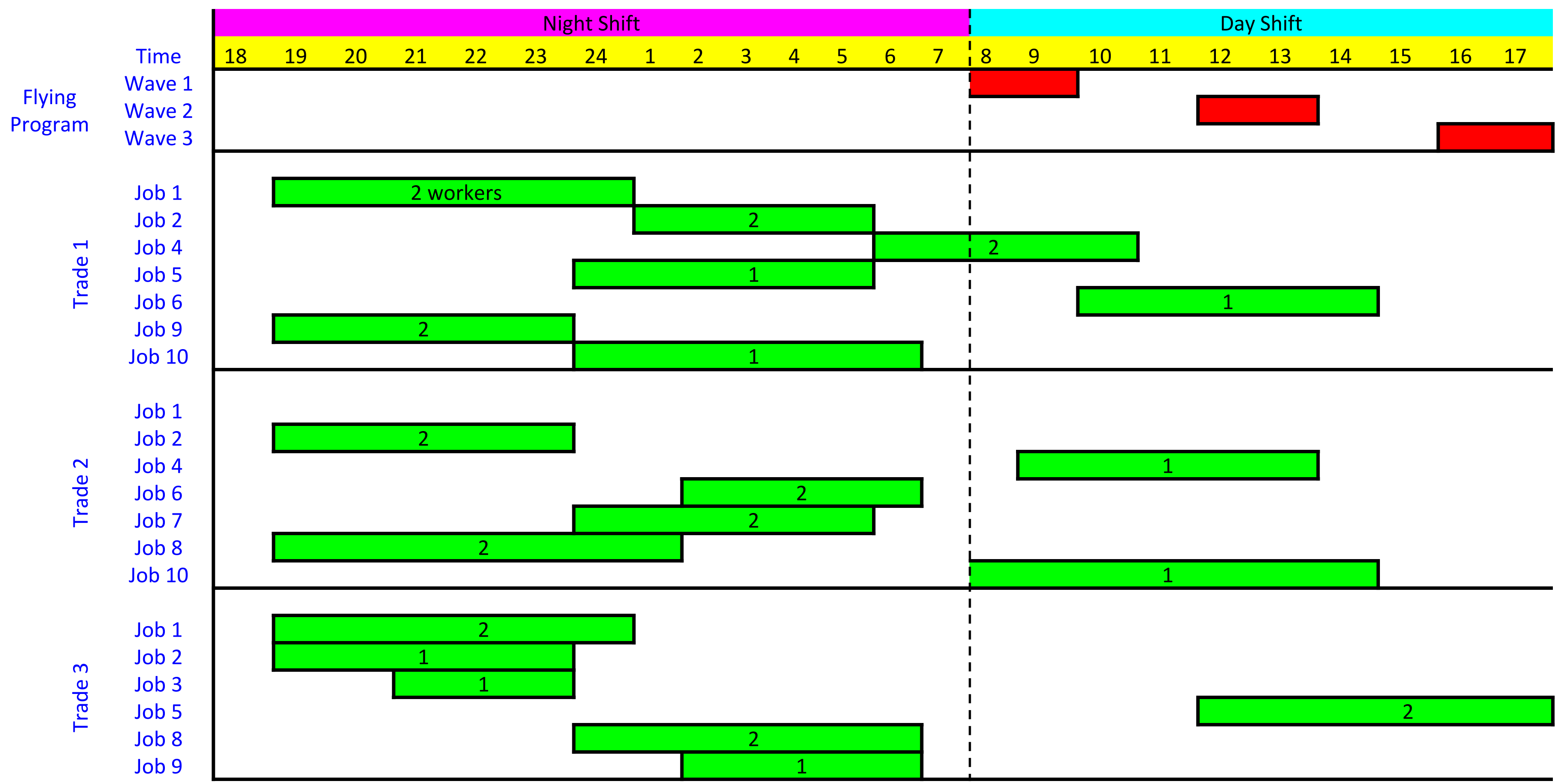
   Fleet availability directly depends on the repair shop throughput $\Rightarrow$

   repair shop productivity directly depends on the effective scheduling of the work orders considering available resources, e.g. workforce, spare parts, tools, and space/slot.

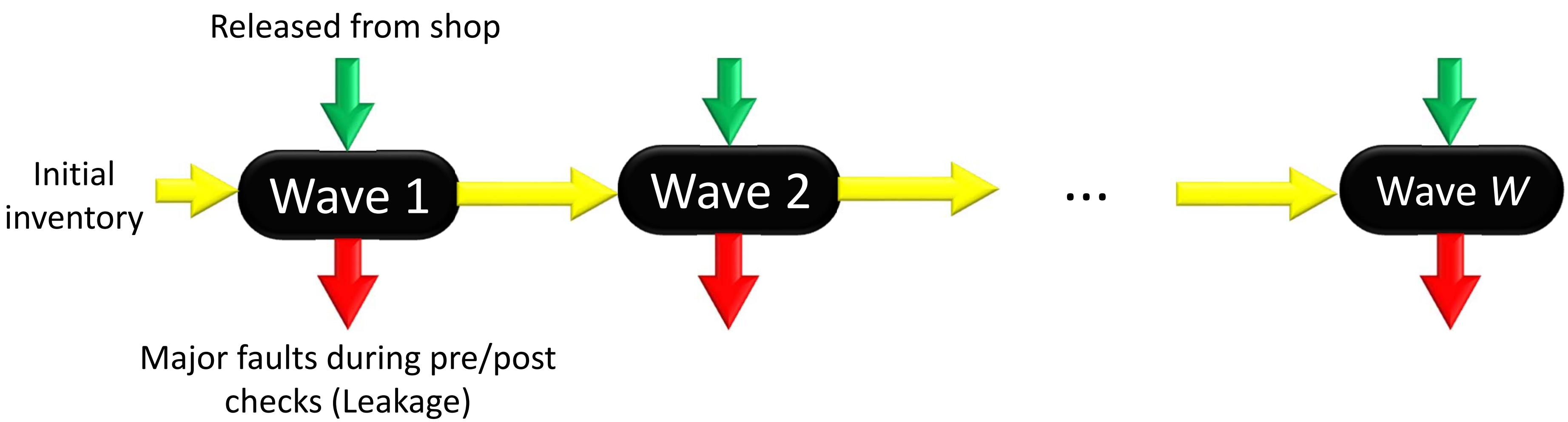
Flight Timing

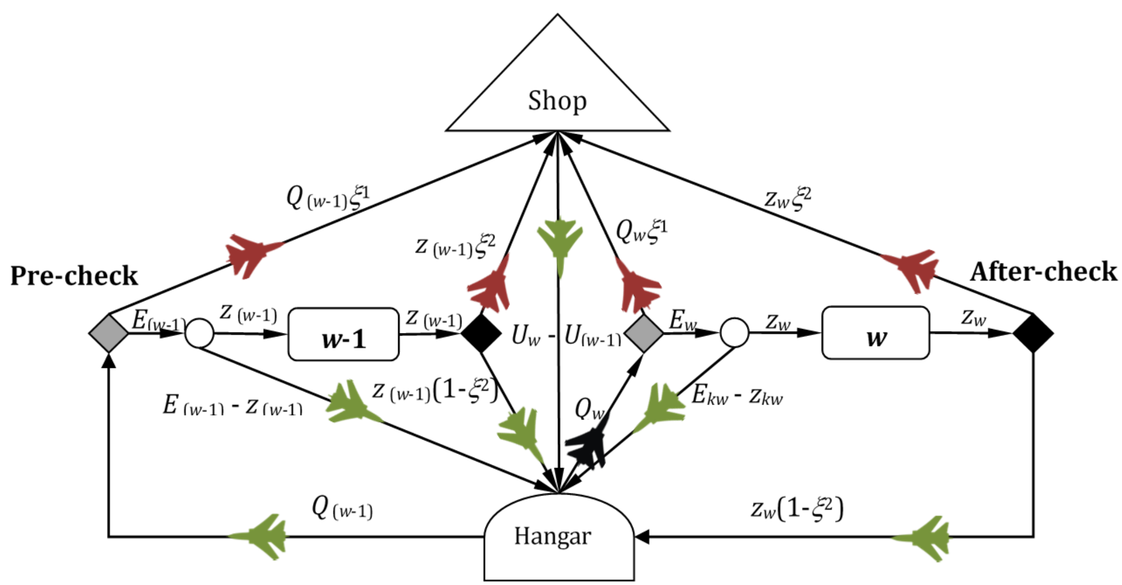


Typical Scheduling
(10 jobs , 3 waves and 3 trades)



Network Flow Strategy





Problem Formulation

Max. δ

Subject to:

- δ = min$_w${Fleet availability for wave w = $\dfrac{\text{No. of assigned aircraft}}{\text{Required No. of aircraft}}$ }
- Classical Scheduling Constraints
- Skilled-workforce availability
- Fleet availability (Network flow Constraints

$$\max Z_1 = \delta,$$

Subject to:

(1)-(3), and

$$\sum_{t=1}^{T} y_{mrt} = 1 \qquad \forall\, m, r; pt_{mr} \neq 0$$

$$\sum_{m=1}^{M} \left(\sum_{s=max\{1,t-pt_{mr}+1\}}^{t} y_{mrs} \right) \lambda_{mr} \leq \lambda_r^{max} \qquad \forall r, t,$$

$$\begin{cases} C_m \geq pt_{mr} + \sum_{t=1}^{T} t y_{mrt} & \forall m, r \\ C_m \leq pt_{mr} + \sum_{t=1}^{T} t y_{mrt} + M^+(1-\alpha_{mr}) & \forall m, r, \\ \sum_{m=1}^{M} \alpha_{mr} = 1 & \forall r \end{cases}$$

$$\begin{matrix} (C_m - ST_w) < (1 - u_{mw})M^+ \\ (C_m - ST_w) \geq -u_{mw}M^+ \end{matrix} \qquad \forall w, m,$$

$$U_w \leq \sum_k \left(\frac{\sum_{m=1}^{M} e_{mk} u_{mw}}{\sum_{m=1}^{M} e_{mk}} \right) \quad \forall w,$$

$$\begin{cases} z_w \leq E_w \\ z_w \leq a_w \end{cases} \qquad \forall w,$$

$$y_{mrt}, u_{mw}, \alpha_{mr} \in \{0,1\};\; C_m, E_w, U_w, z_w \in \mathbb{Z}^+.$$

Typical Input– CMMS Databases

Aircraft Type (k)	Failure Mode		Task Duration (log-normal distribution)			Required # of Tech.			Probabilities		
	Category	No. (i)	WP	AF	AV	WP	AF	AV	P_{ki} (Poisson distribution)	θ_{ki} (Discrete scenarios)	ξ_k
1	WP	1	3	0	3	2	0	2	0.27	0.76	0.209
	WP	2	3	5	0	2	2	0	0.27	0.45	
	AF	3	2	6	0	0	2	0	0.25	0.75	
	AF	4	3	7	0	2	2	0	0.25	0.57	
	AF	5	0	5	3	0	2	2	0.25	0.03	
	AF	6	0	4	2	0	2	0	0.25	0.98	
	AV	7	0	1	5	0	0	2	0.17	0.25	
	AV	8	0	4	6	0	2	2	0.17	0.93	
	AV	9	3	0	5	2	0	2	0.17	0.6	
	AV	10	0	3	4	0	2	2	0.17	0.12	
2	WP	1	3	0	2	2	0	0	0.27	0.96	0.264
	WP	2	4	3	0	2	2	0	0.27	0.95	
	WP	3	3	2	0	2	0	0	0.27	0.08	
	AF	4	0	6	2	0	2	2	0.25	0.11	
	AF	5	3	6	0	2	2	0	0.25	0.26	
	AF	6	4	7	0	2	2	0	0.25	0.49	
	AV	7	1	0	3	2	0	2	0.17	0.93	
	AV	8	0	4	4	0	2	2	0.17	0.7	
	AV	9	2	0	5	0	0	2	0.17	0.99	
	AV	10	0	1	6	0	2	2	0.17	0.18	

P_{ki} = Probability that the failure mode i of aircraft type k is detected during the pre- or after-flight check (Poisson distribution - *probability of a number of independent events occurring in a fixed time*)

θ_{ki} = Probability that the failure mode i of aircraft type k is a major fault (based on discrete scenarios)

ξ_k = probability that a major fault is detected during the pre-flight check

Numerical Example

Maintenance Jobs Information

Job No.	1	2	3	4	5	6	7	8	9	10
Aircraft Type (*k*)	1	1	1	1	1	2	2	2	2	2
Failure mode (*i*)	2	4	6	8	10	1	3	5	7	9

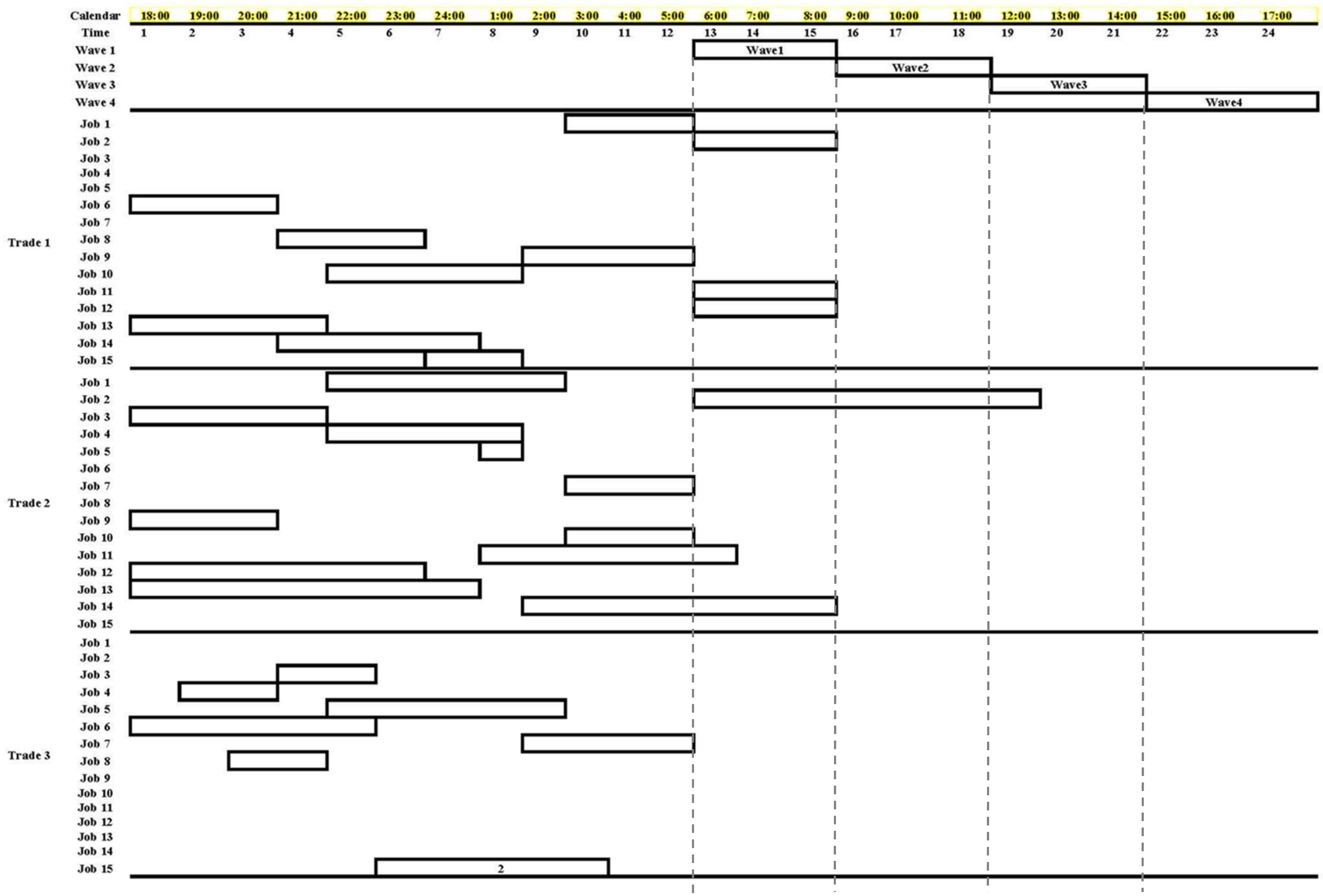
Flying Program

Wave No.	Stating time	Ending time	Aircraft Type 1	Aircraft Type 2
1	8:00 am	11:00 am	3	3
2	11:00 am	14:00 pm	3	3
3	14:00 pm	16:00 pm	3	3
		Initial Inventory at hanger	1	1

Model output for different levels of workforce availability

Workforce Availability			Completion time (hrs)										Fleet Availability		
λ_1^{max}	λ_2^{max}	λ_3^{max}	1	2	3	4	5	6	7	8	9	10	W1	W2	W3
2	2	2	24	6	11	16	21	10	17	17	24	5	1	0.84	0.84
4	2	2	14	13	24	5	21	17	17	19	7	14	1	0.84	1
2	4	2	24	6	17	21	5	20	14	17	12	16	1	0.84	1
2	2	4	17	24	17	12	14	11	21	8	11	13	1	1	0.84
2	4	4	14	24	14	5	17	17	21	14	17	5	1	1	0.84
4	2	4	8	24	10	17	6	3	12	18	16	14	1	1	0.84
4	4	2	17	17	14	24	8	19	15	3	14	13	1	1	0.84
4	4	4	3	21	11	10	15	12	21	9	17	8	1	1	1

A Typical Optimal Schedule



Case Study 3:

Electricity Transmission & Distribution

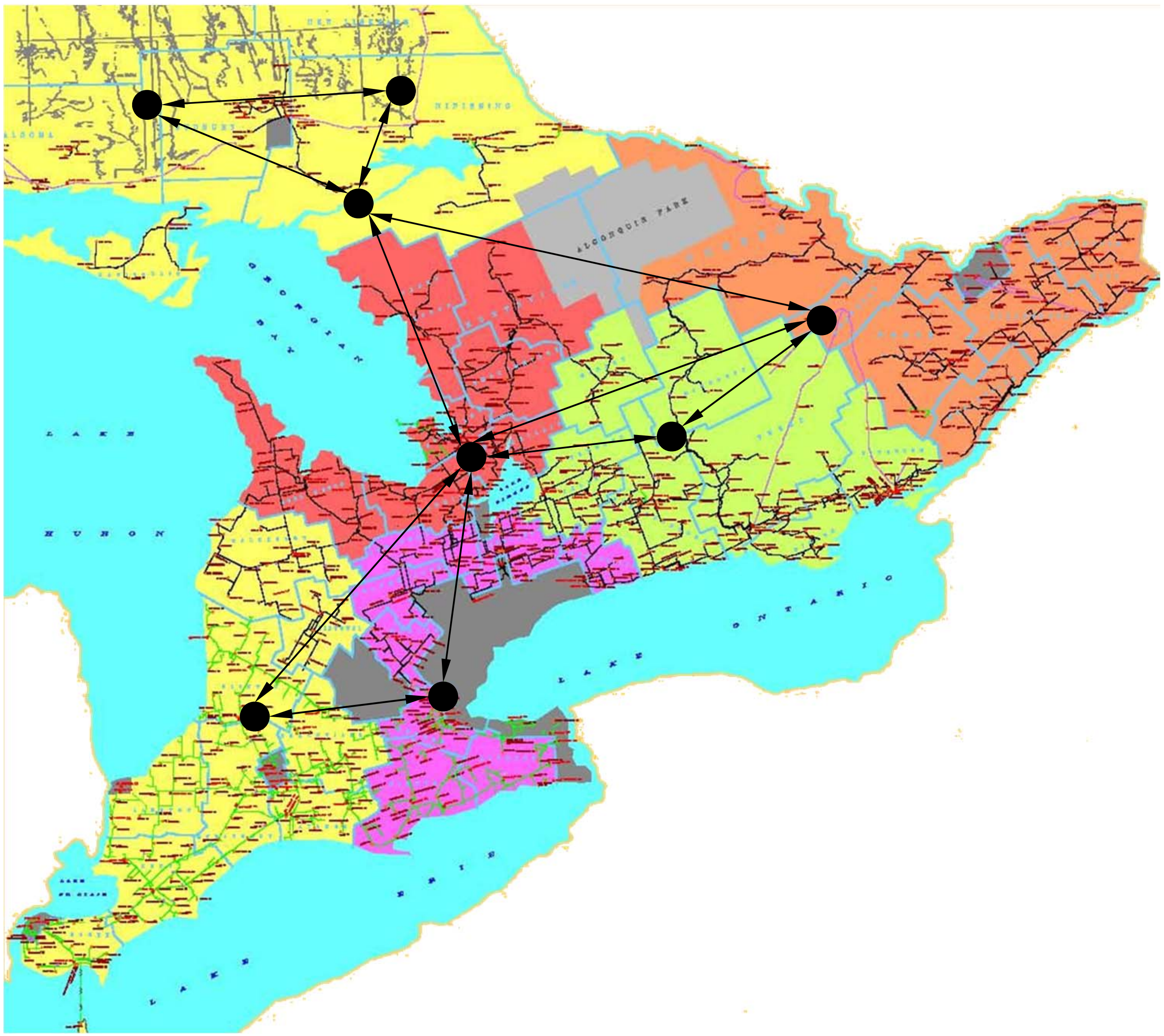
Safaei, N., Banjevic, D. and Jardine, A.K.S., Workforce Planning for Power Restoration in Electricity Delivery Industry: an Integrated Simulation-Optimization Approach, to be appeared in ***IEEE Transactions on Power Systems***, 2011.

Background

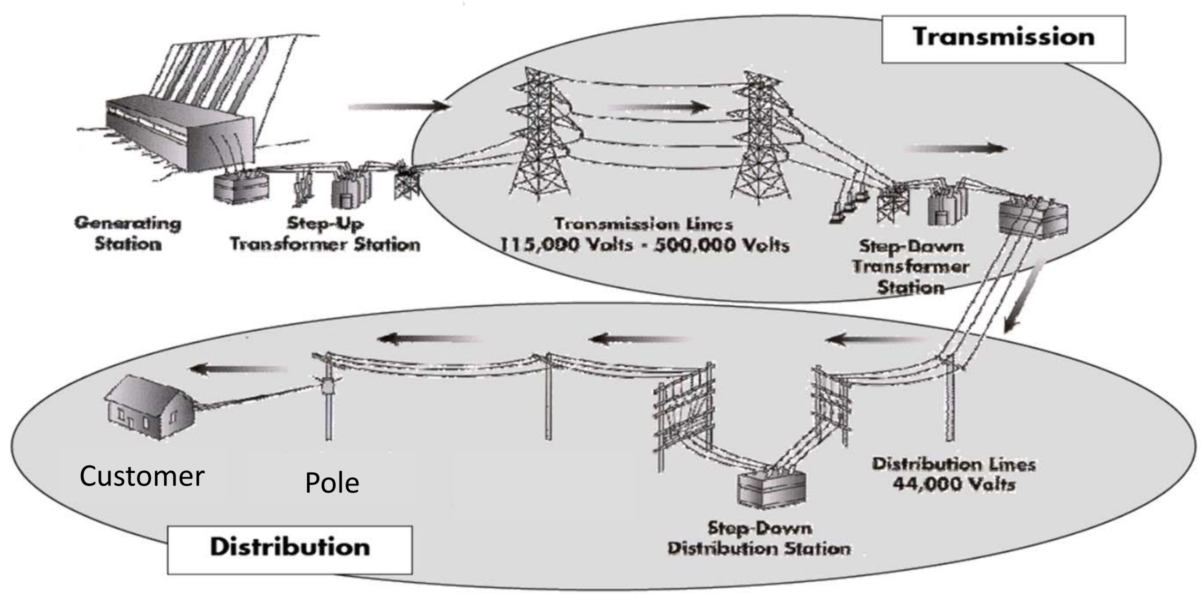
1. One of the largest electricity delivery systems in North America with almost 30,000 km of transmission lines and 122,000 km of distribution line directly serve about 1.3 million customers.
2. There is nearly 40,000 annual power interruptions.
3. Power interruptions may be caused by trees, equipment failure, natural disasters (e.g., storm, freezing rain, etc), fire or collision.
4. The problem is to provide the required workforce for restoring interruptions with minimum workforce cost and response time, or equivalently the maximum customer satisfaction.
5. The restoration of power interruptions must be done in **4 hours**.

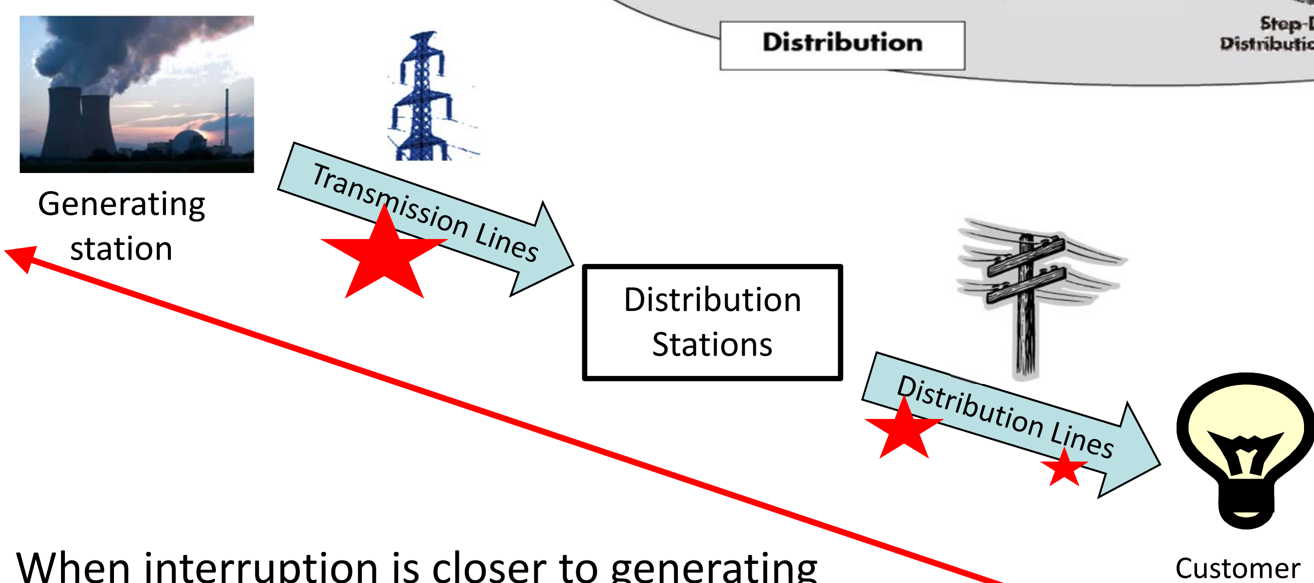
Company’s Distribution Network

(50 Operating Centers at 8 Geographical Regions)



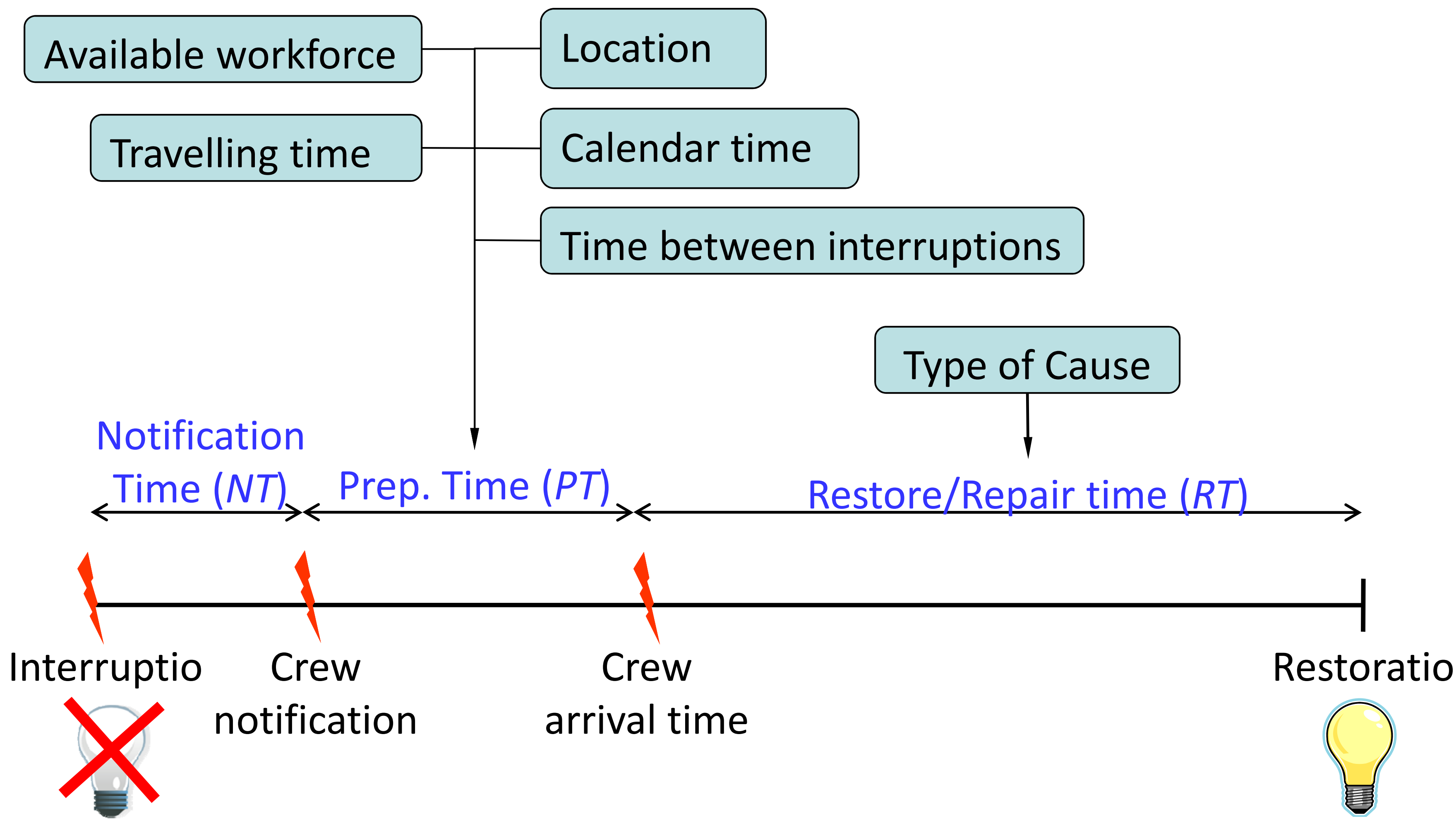
Electricity Distribution System Overview





When interruption is closer to generating station, number of customers affected increases

Power Restoration Timeline

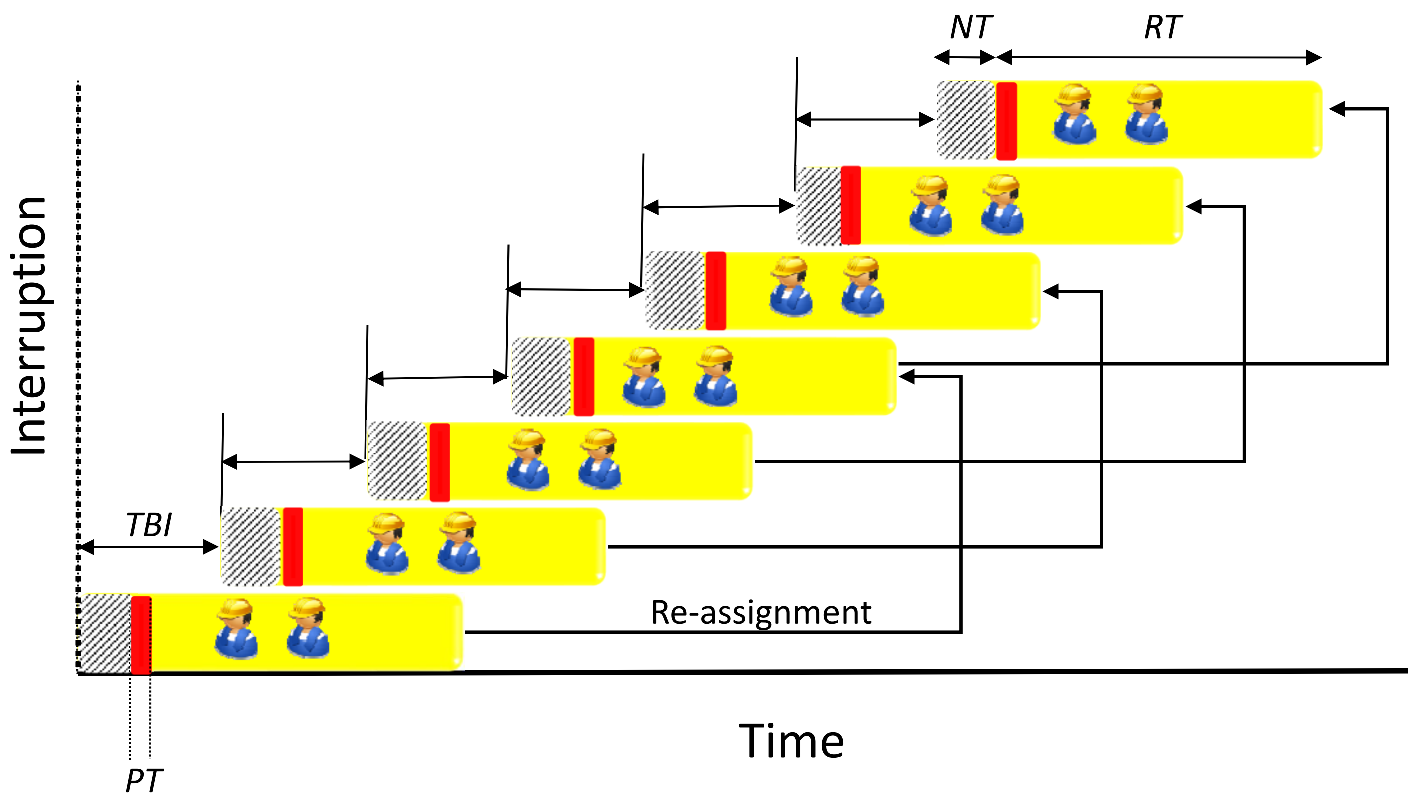


Causes of Power Interruption

No.	Cause	Frequency of Interruptions (%)
1	Scheduled (PM actions)	11.55
2	Loss of supply	0.41
3	**Tree Contact**	**29.54**
4	**Defective Equipment**	**39.81**
5	Human Element (Collusion,…)	1.20
6	Foreign Interference	11.89
7	Adverse Environment	0.03
8	Non Interruption	0.11
9	Unknown/Other	5.47
Total #		**179,550**

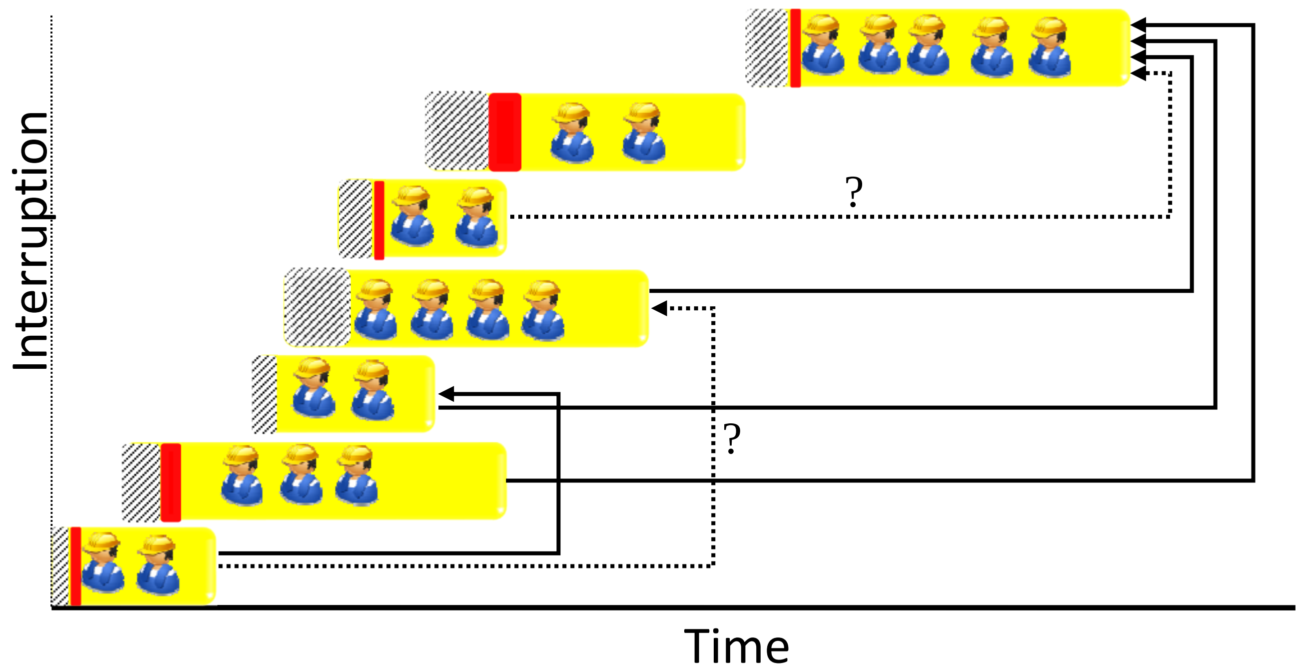
Restoration Tasks Scheduling
(under Deterministic/Ideal Conditions)

TBI = time between interruptions
PT = Preparation time
NT = Notification Time
RT = restoration Time

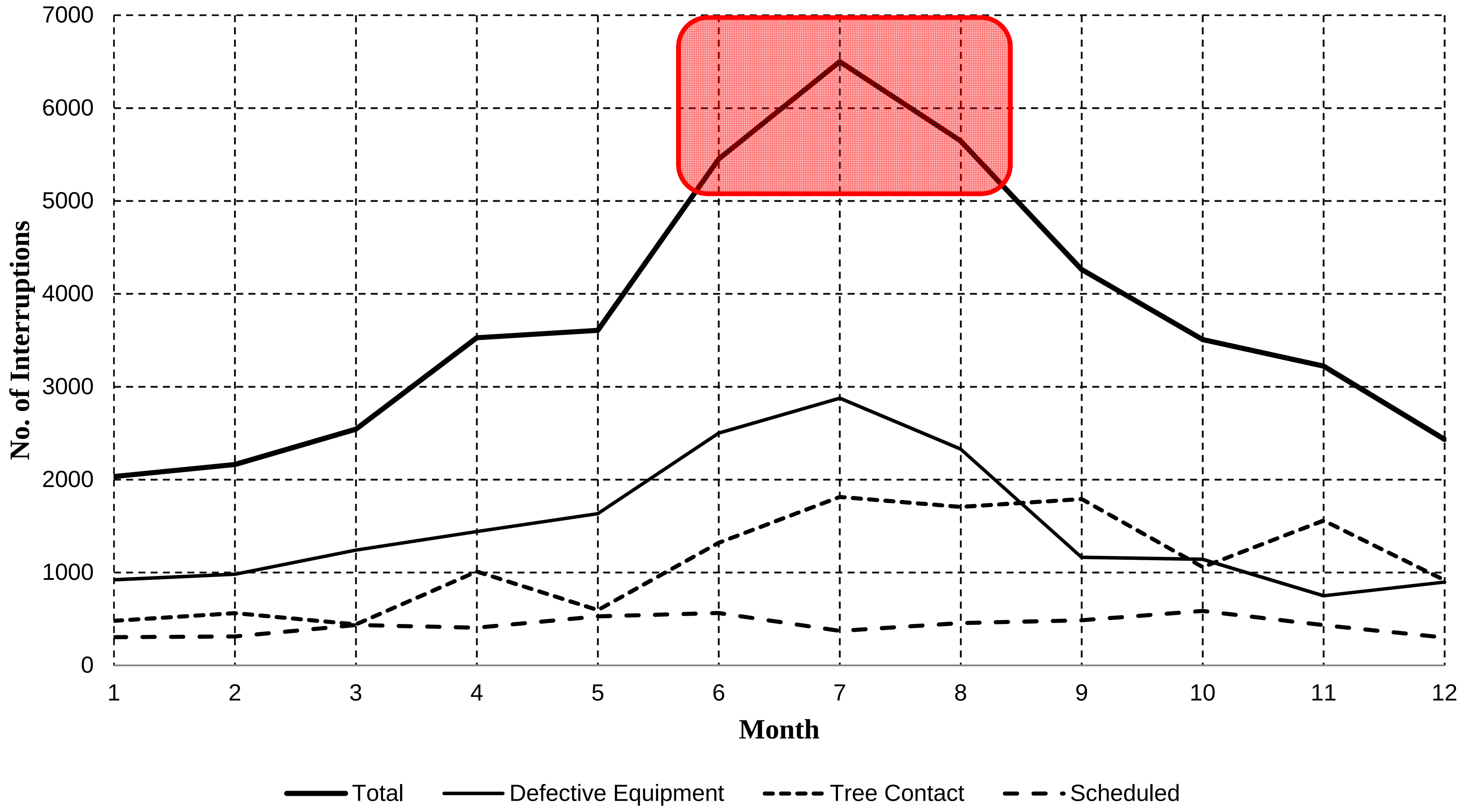


Restoration Tasks Scheduling

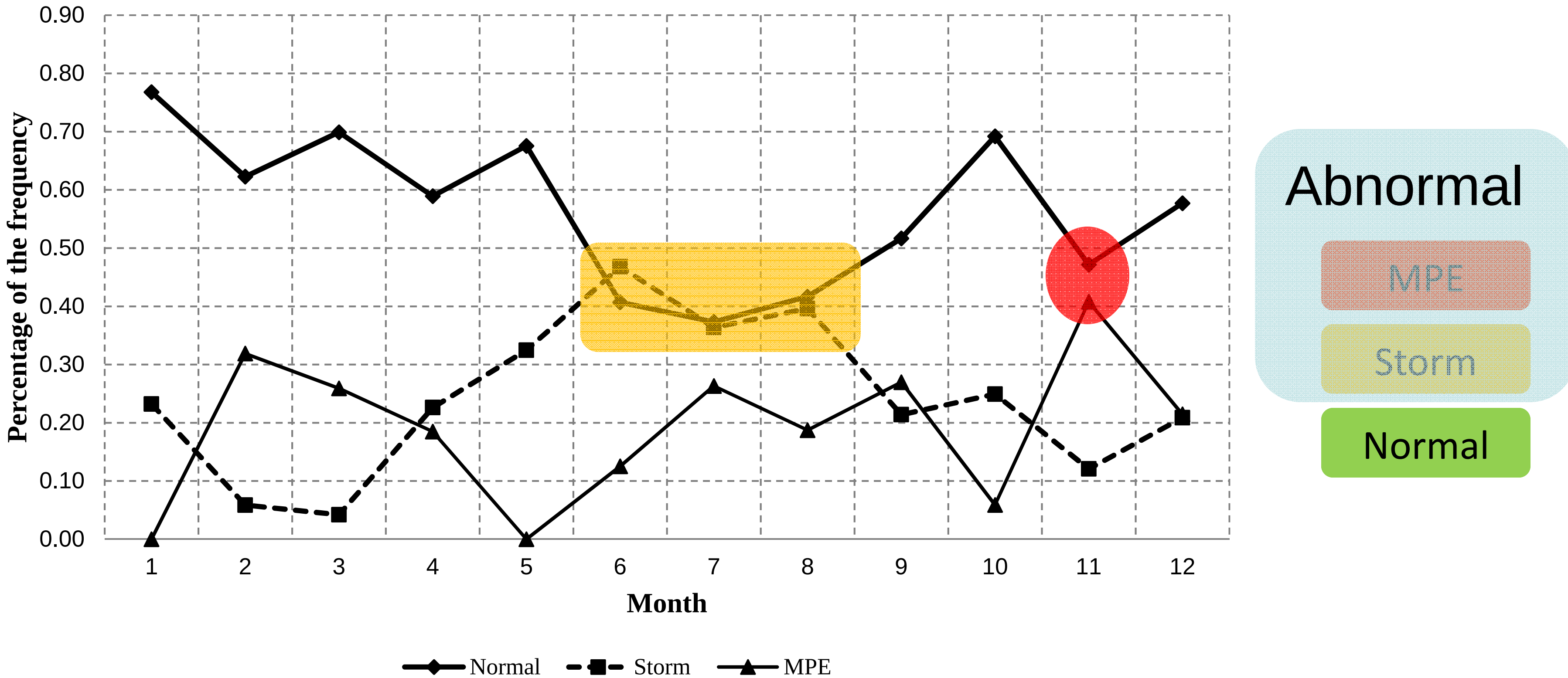
(under Uncertainty Conditions)



Frequency of Causes versus Calendar Time

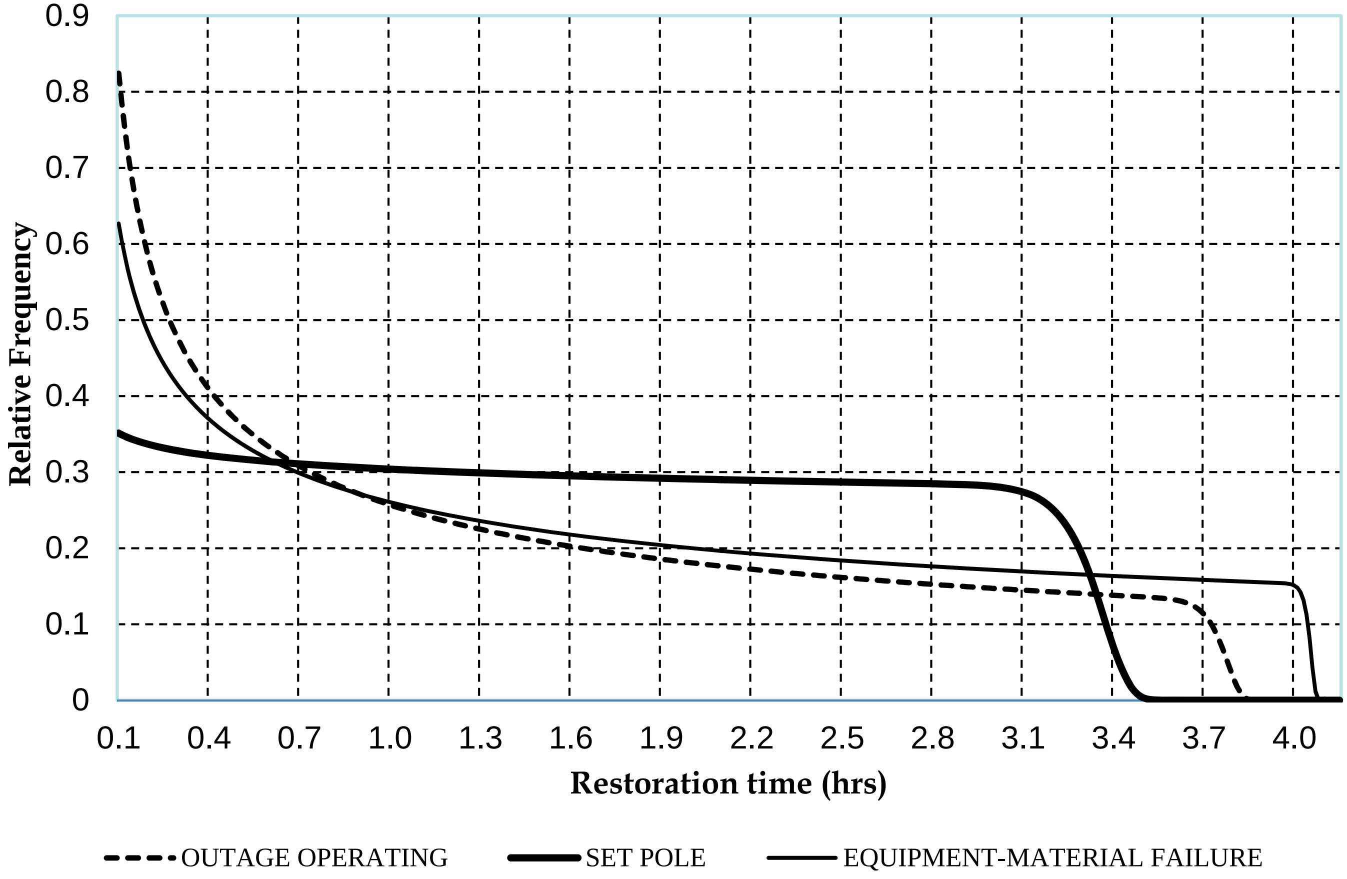


Interruption Frequency under Various Weather Conditions



* MPE: Most Prominent Event

Limited Interruption Duration



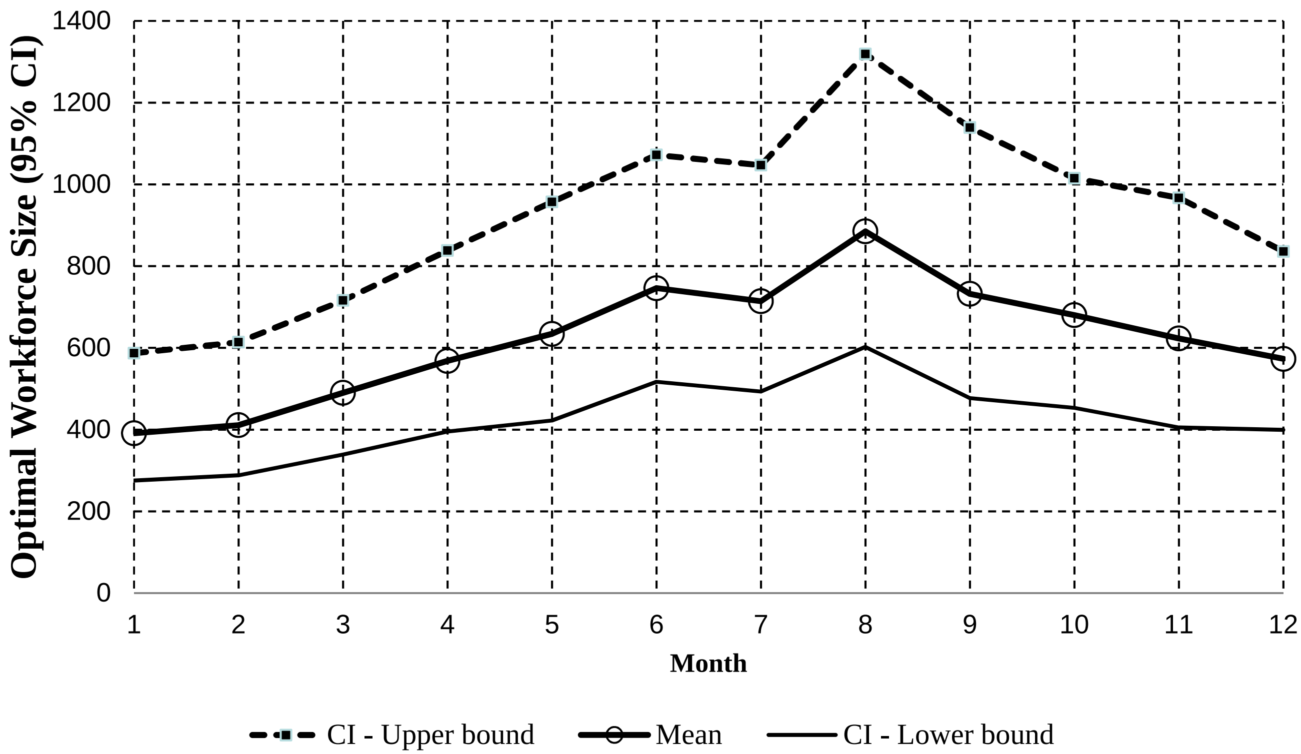
The data analysis reveals that the crews have attempted to keep the restoration time less than 4 hours (*G-Gamma* distribution)

Monte-Carlo Simulation

to Calculate the Workforce Size under the Worst-case Scenario

Assumptions:

- there is a large enough labour resource at the time of interruption. Thus, the restoration task is not delayed or postponed due to a workforce shortage – Thereby the PREP time is considered to be negligible.
- Notification time (NT) is a random variable with unknown pattern (uniform Dis.)



Workforce Assignment Optimization

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Internal	470											
External (Normal)	71	62	77	140	177	283	278	428	283	219	183	182
Additional External resource (Abnormal)	54	92	169	228	310	319	299	421	386	326	314	184
Total demand	595	624	716	838	957	1072	1047	1319	1139	1015	967	836
# of relocated people (Abnormal)	64	40	17	13	1	0	17	0	5	0	7	38

- Average gap between the obtained Internal workforce size assigned to each operating center and current situation = 6 ±4% (95% CI)
- Current available resource is nearly sufficient to satisfy the **normal** situations.
- The assignment of workforce to operating centers at present is not optimal.
- Current available resource would enable the company to handle the **abnormal** events in months January, February, March, April, and December, if the optimal assignment presented in this research were applied.
- To handle the **abnormal** events with possible minimum risk during rest of the year, the company should employ more external resources and also use the workforce **relocation option** in accordance with the outcome of this research.

Optimal Workforce Relocation

Region 1	15	26	33	36	43	46	48	49	50
15									1(11)
26			3(12)						
33									
36			2(12)		2(2)	1(3)		1(2)	
43									
46					1(2)				
48	1(1) , 1(12)			2(1)					
49	2(1)								
50	5(1)		5(2)			3(12)	3(3)		

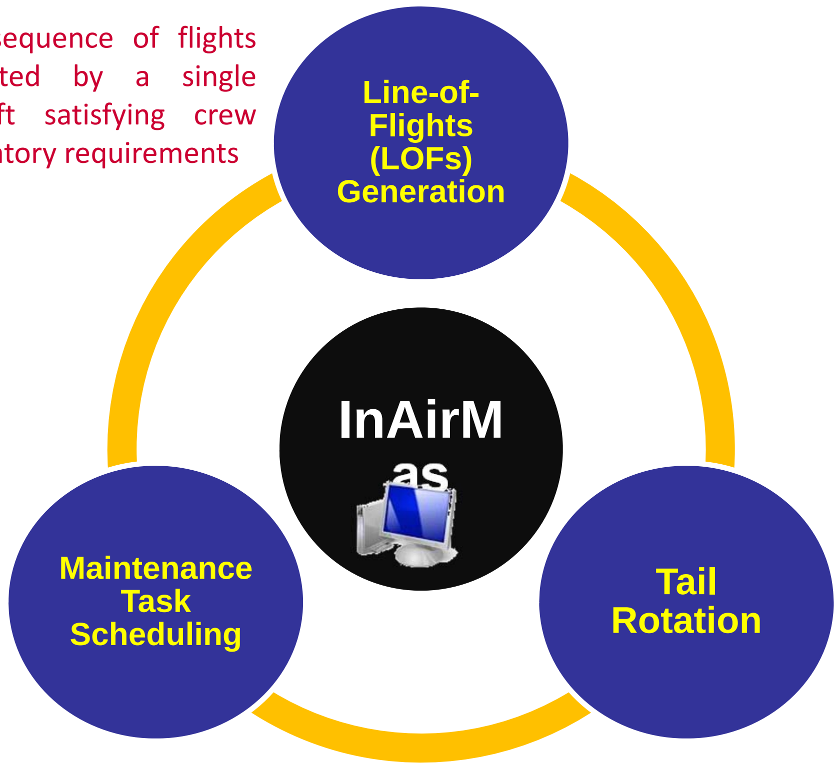
Region 5	4	5	27	30	34	37	38	44
4			3(4)					
5	5(1) , 5(12)		9(1) , 3(4)	6(12)		1(1) , 1(4) , 6(12)	1(1)	2(1) , 5(6)
27							2(2) , 6(12)	1(2)
30						2(3)	2(4)	1(4)
34							1(1)	3(4) , 3(12)
37							1(2)	1(8) , 1(9)
38								
44							2(3)	

Case Study 4:

Aircraft Rotation and Maintenance Scheduling

Integrated Aircraft Routing & Maintenance Scheduling (InAiRMaS)

The sequence of flights operated by a single aircraft satisfying crew regulatory requirements



What maintenance tasks should be done on which aircraft at which maintenance station and when?

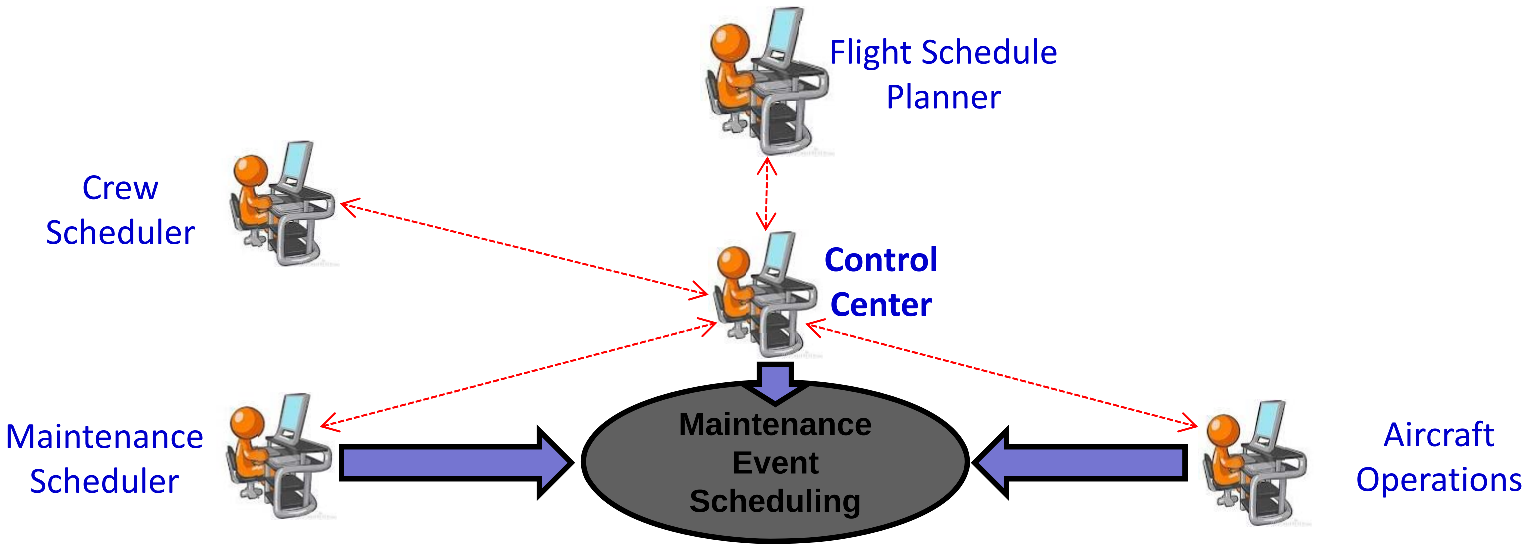
The sequence of LOFs operated by a particular aircraft.

- InAirMas ensures that the **right aircraft** is in the **right place** at the **right time** to undergo maintenance.
- With InAirMas, the fleet will spend more time in the air, earning revenue, reduce the maintenance costs, increase the dispatch reliability, and mitigate the flight interruptions impact.
- Efficient and automatic **interaction** embedded in InAirMas enable us to **optimally coordinate** various functions **at the same time.**
- **Powered by** advanced optimization algorithms, predictive analytics, and artificial intelligence.

Aircraft Approved Maintenance Program

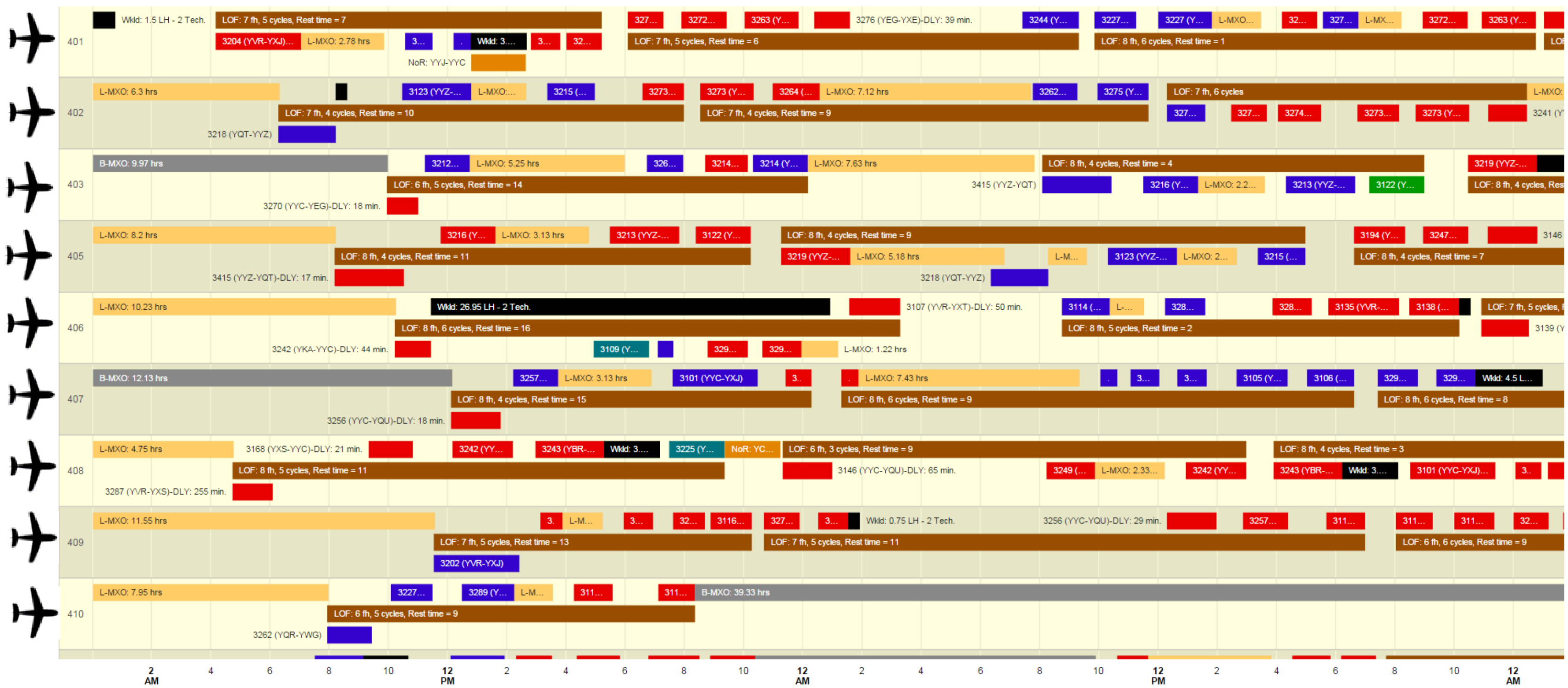
- **Service & Routine Checks:** General visual inspection
  - ❑ Every 36, 50, 65, and 100 **FH**
- **Line Check (Type A):** Detailed visual inspection, lubrication
  - ❑ Every 600, 1200, 1800, 2400, 3000, and 3600 FH
- **Base Check or Heavy/Hanger Maintenance (Type C):** Detailed inspection, Restoration, and discard
  - ❑ Every 6000, 12000, 18000, 24000, 30000 FH
- **Calendar Check**
  - ❑ Every 1, 6, 12, 24, 36, 60, 72, 108, 120 and 180 **Months**
- **Out of Phase Items:** inspections, certification or warranty requirements which do not fall on the same date as the annual inspections
- **Out of Service Items (Unscheduled MX)**: MX work that has not been included on the approved MX Schedule prior to its commencement.
  - ❑ Ranged between 200 to 40000 FH
- **Fatigue Tasks:** fatigue damage detection and correction
  - ❑ Ranged between 250 to 100,000 **FC**
- **½ Life Check:** A conservative overall inspection program based on economic life of aircraft.

Current Practice



- Each group has own KPIs, priorities and processes
- Insufficient coordination and harmonization between the groups
- Up to **80%** of the tasks in OCC and MCC are manually performed based on individual knowledge.
- In general, the software packages are used for visibility and feasibility check not for **integration** and **optimization**.
- Significant gap between the initial long-term plan provided by NSP and short-term schedules created by OCC (coordination between the groups).
- Reliability group's concern: Increased fleet utilization has a negative effect on non-chargeable interruptions

Aircraft Maintenance Routing - Gantt Chart



On-time flight

Delayed flight

Early flight

Cancelled flight

Diverted flight

Non-revenue flight

Line-of-flight (LOF) satisfying crew regulatory requirements

Scheduled maintenance check (M-H)

Base maintenance opportunity (M-H)

Line maintenance opportunity (M-H)

Thank You

Q&A