Improving the Landside Operation of a Container Terminal by an Intermediate Stacking Area

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Combinatorial Optimization at Work, Beijing 2006

DFG Research Center MATHEON Mathematics for key technologies
Modelling, simulation, and optimization of real-world processes

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"Mathematics for key technologies"

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Capacity: 700,000 TEU

Trade growth:

7.5% per annum

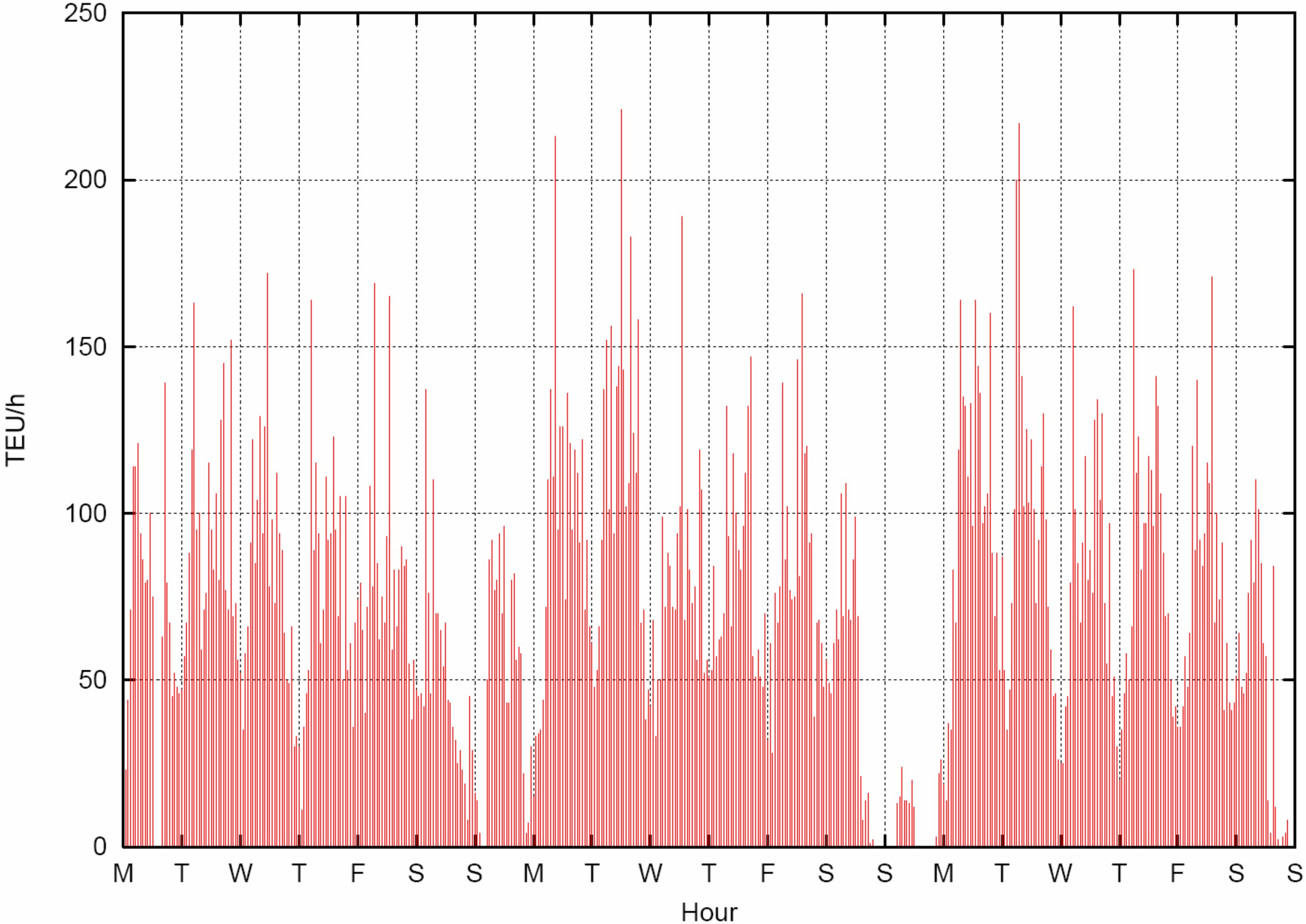
2005 throughput:

>800,000 TEU

Old Landside Operation

September 2005

Landside Turnover per Hour



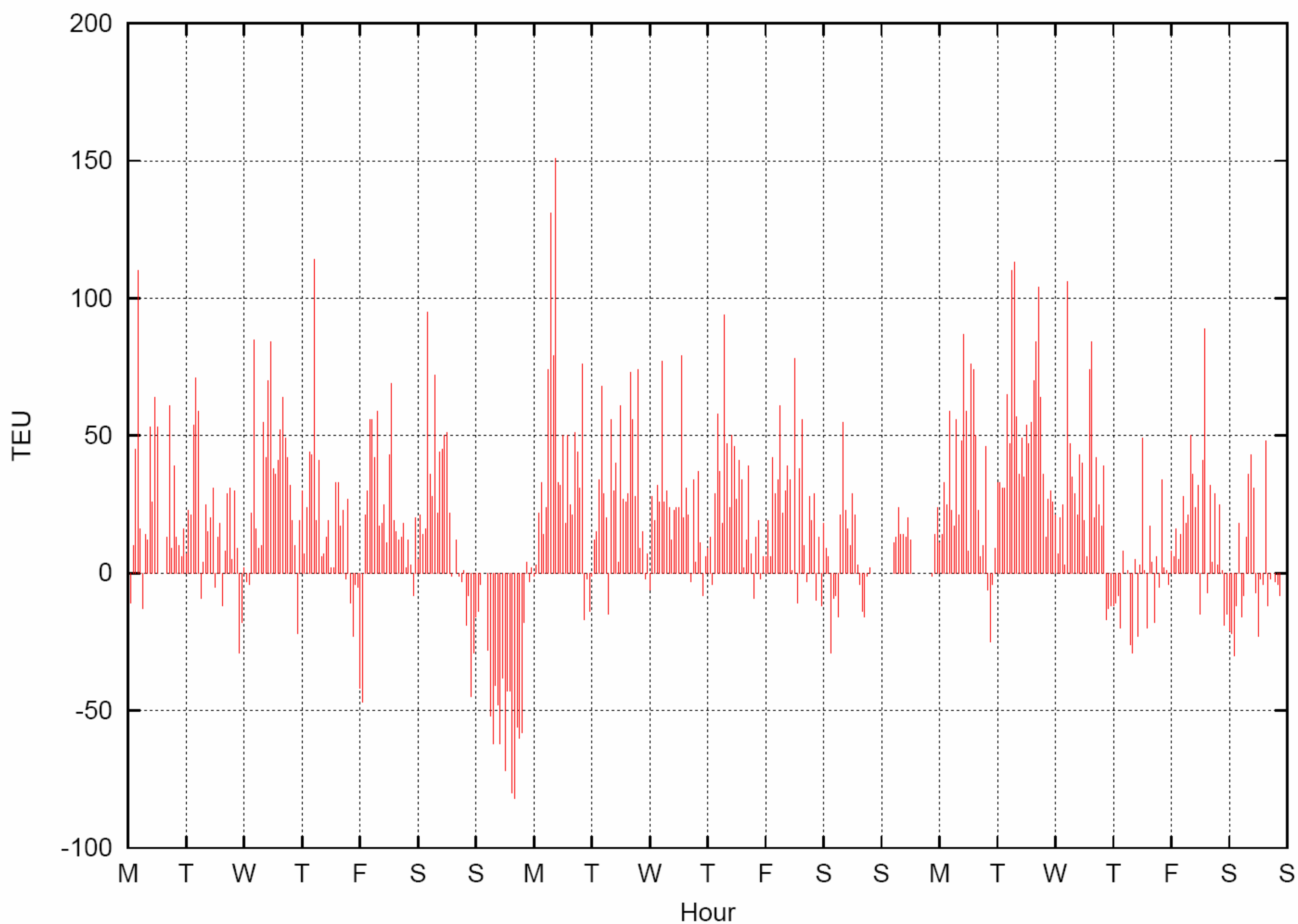
Min 0

Avg ~80

Max >200

Container movement is done by a fixed number of straddle carriers.

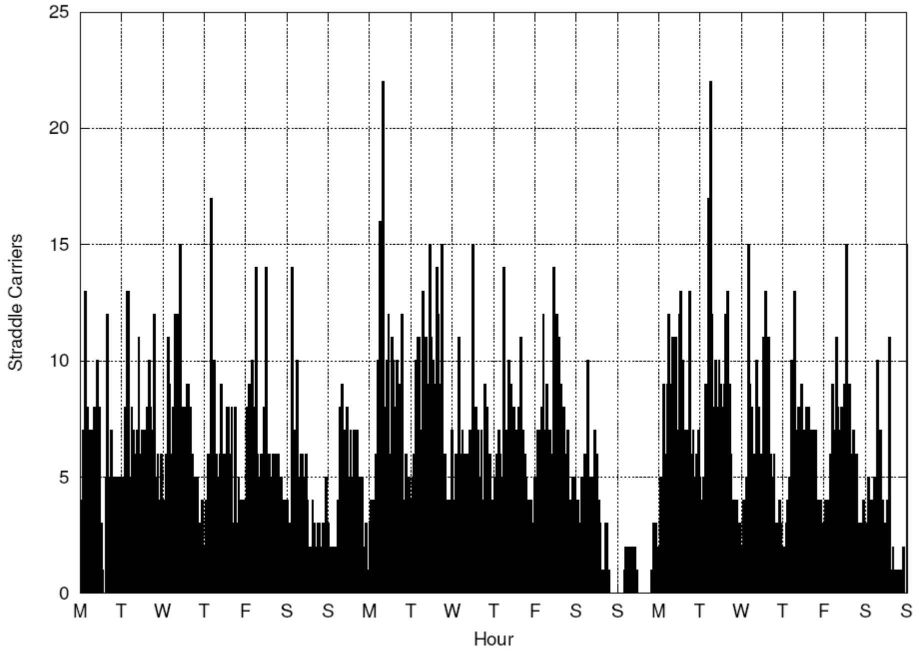
Import minus Export per Hour



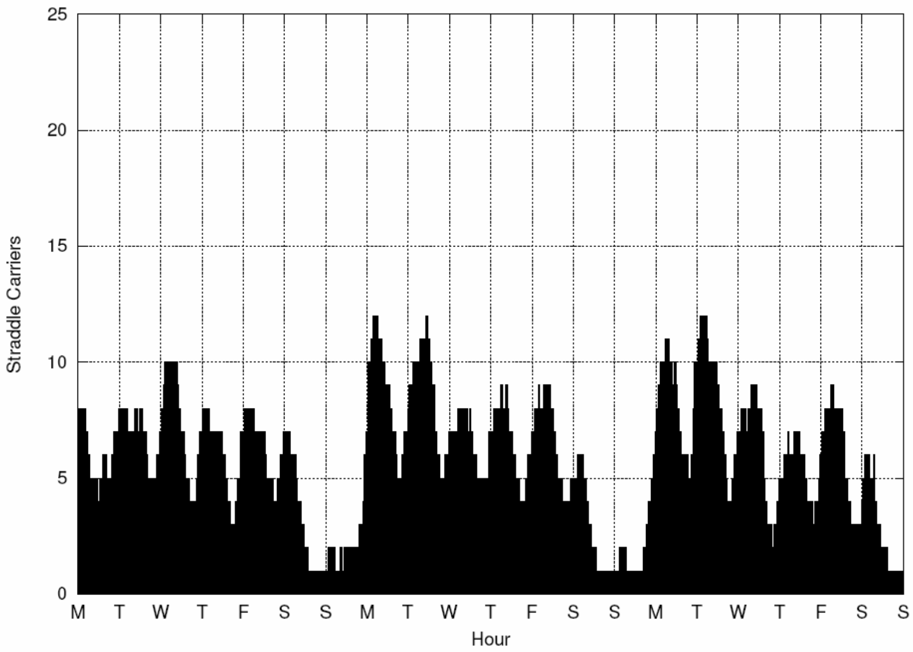
The straddle carriers can be most efficiently utilized if the same number of containers is arriving and departing in each hour.

Straddle Carriers needed assuming optimal pairing

1 hour average

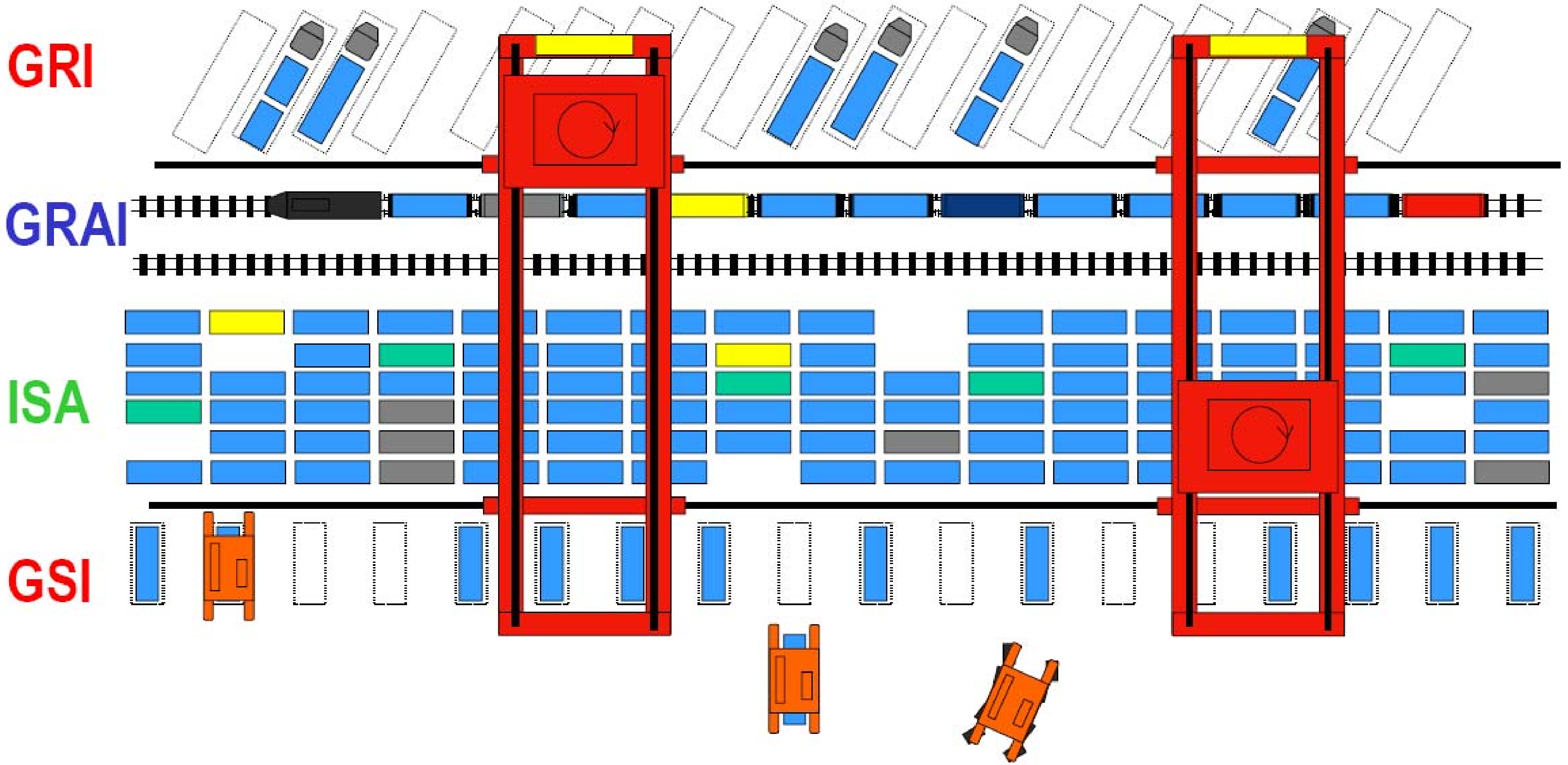


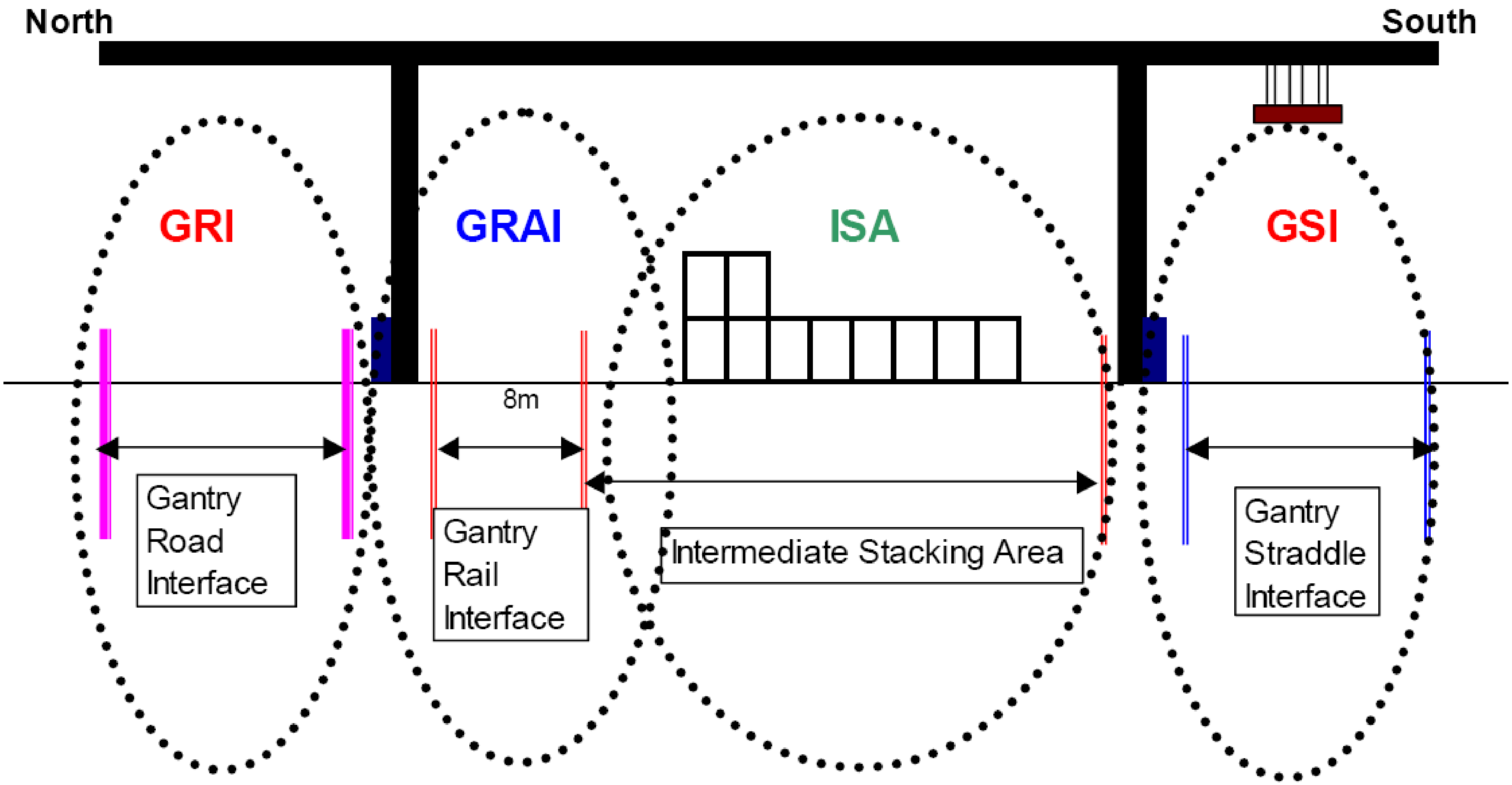
8 hour average



Space needed: 8 h $\times$ 12 carriers $\times$ 6 trips $\times$ 2 directions $\times$ 1.43 TEU $\approx$ 1600 TEU

New Terminal Design with Intermediate Stacking Area





5 Rail Mounted Gantry cranes (RMGs)

60 Truck bays at the Gantry Road Interface (GRI)

100 columns × 7 rows × 3 stacks = max. 2100 TEU Intermediate Stacking Area (ISA)

Max. 792 TEU Gantry Straddle Interface area (GSI)

The Data

- 1 month of historical data
- Slightly less than 50,000 TEU
- 60% imports
- 57% 20' containers both in import and export
- Each truck either delivers of picks up a single container
- Trains are converted to trucks

Import means coming from a ship going into Australia

Export means going to a ship leaving Australia

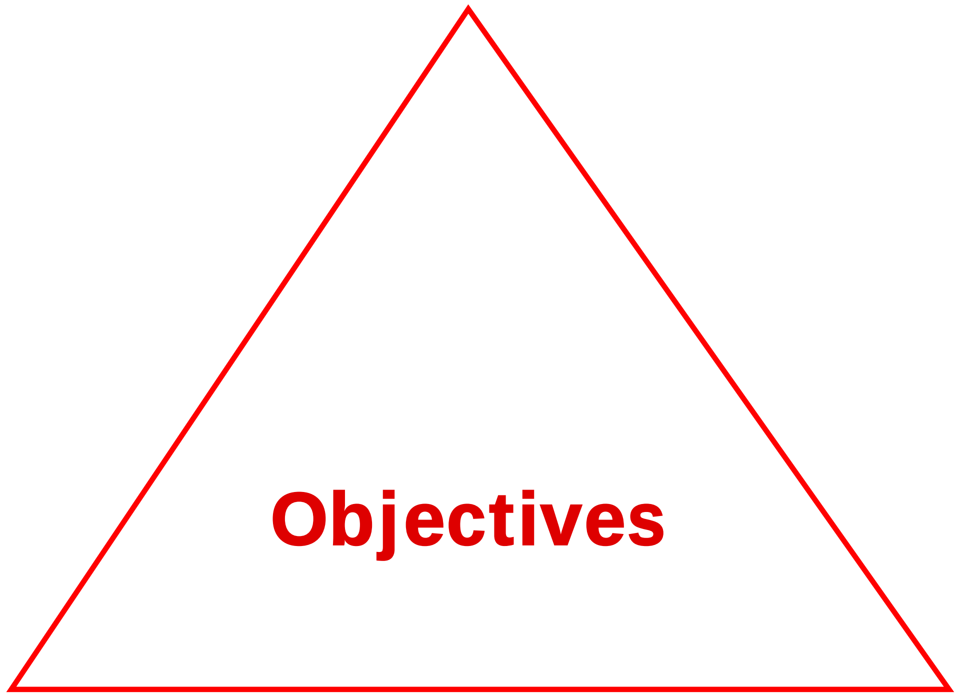
The Rules

- Export containers have to be delivered to the yard 12 hours before ship arrival. (Direct export is possible)
- Import containers have to be present in the ISA 4 hours before truck arrival. (Direct import is not allowed)
- Trucks have to book their arrival (both for import and export) in advance for a certain hour.
- The order of truck arrivals within an hour is unknown beforehand.
- No special handling for Reefer or other special containers

The Objectives

- Getting a feasible schedule
  (Trucks should not wait more than 15 minutes)
- Minimize the maximum number of straddle carriers needed
- Maximize the possibility for pairing straddle operations
- Balance the total RMG load from hour to hour
- Balance the load between the RMGs within the hour
- Minimize the total usage of the RMGs

Minimizing the number of needed straddle carriers



Balancing RMG utilization

ISA utilization

The Plan: Decomposition into three Phases

- Strategic planning
  temporal assignment of container movements to hourly time slots
  → done by integer program

- Tactical setup
  assignment of import containers to GSI positions
  → done by integer program or simple algorithm

- Operational decision-making
  assignment of containers to ISA positions, of export containers to GSI positions, and trucks to GRI positions.
  Planning of precise RMG movements within the hour.
  → done by online algorithm

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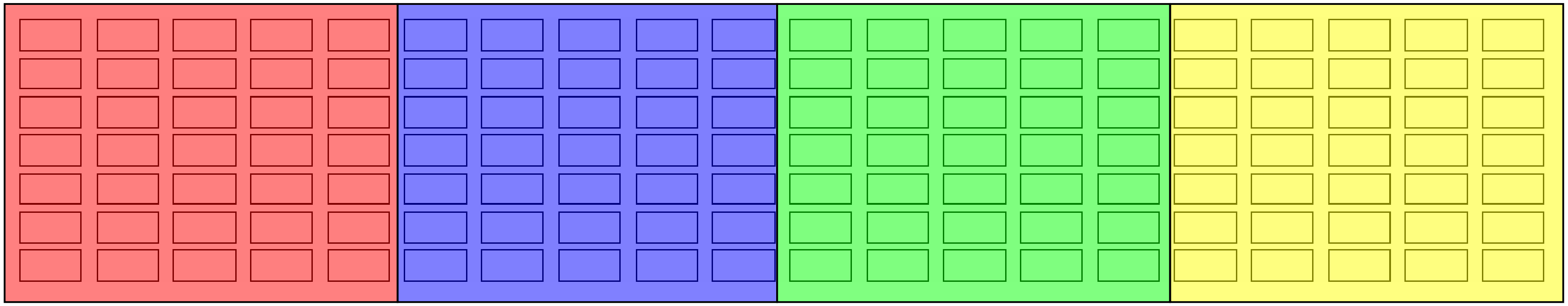
The Idea: Hiding Cross-travel Time by Space-Time Divisioning

- Each RMG gets an exclusive moving area of 20 columns.
- For each hour we try to restrict each RMG to a corridor of 5 columns within its moving area.
  The 4 corridors cycle, so every 4 hours the same corridor is used.
- The RMGs can long and cross travel at the same time. While moving from GRI to GSI it can move about 5 columns cross at no cost.

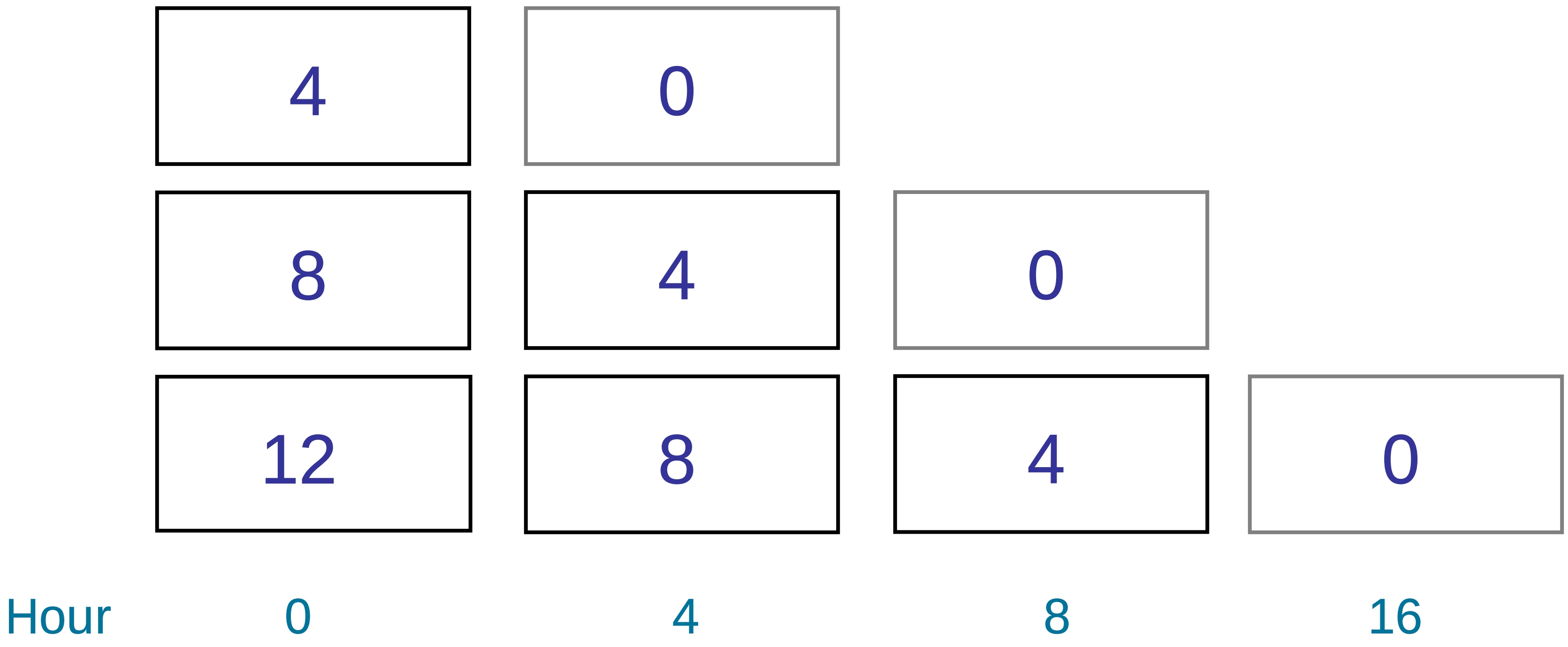


Difficulties in Stacking

or why packing is sometimes inevitable

Assume a truck picking up an import container has to book its arrival 12 hours in advance.

Note: Each container has to be moved to the ISA at least 4 hours before the truck arrives.



Objectives of the strategic IP

- Assign each container a GSI movement time within its allowed time window.
  The GSI movement and the GRI (Truck) movement time should match the same moving corridor.
- The maximum number of straddle carriers needed for an hour should be minimized assuming optimal pairing.
- The load of the RMGs between hours should be balanced and stay within reasonable limits.
- The utilization of the ISA has to stay within limits.

Find a schedule that gives the online algorithm a chance to succeed.

Data for the strategic IP

H	set of hours $\{1,\ldots,\mathscr{H}\}$
C	set of containers transiting GRI
C_h	$\subset C$, subset of containers transiting GRI in hour $h \in H$
I	$\subseteq C$, import containers
E	$\subseteq C$, export containers, $I \cup E = C$, $I \cap E = \emptyset$
I_h	$:= C_h \cap I$, import containers transiting GRI in hour $h \in H$
E_h	$:= C_h \cap E$, export containers transiting GRI in hour $h \in H$
W_c	$\subseteq H$, set of available hours for GSI movement by RMG for container $c \in C$ (time window in GSI)
L	set of RMG utilization levels $\{1,\ldots,\mathscr{L}\}$
M	set of ISA utilization levels $\{1,\ldots,\mathscr{M}\}$

λ_l	$\in \mathbb{N}_+$ Number of RMG operations below utilization level $l \in L$, $\lambda_l < \lambda_{l+1}$
μ_m	$\in \mathbb{N}_+$ Number of containers below ISA utilization level $m \in M$, $\mu_m < \mu_{m+1}$
τ_c	TEU count of container $c \in C$ (either 1 or 2)
$\tau(X)$	$\sum_{c \in X} \tau_c$, $X \subset C$.

Variables of the strategic IP

Define variables $x_{ch} \in \{0,1\}$ with $c \in C$ and $h \in W_c$.

$$x_{ch} = \begin{cases} 1, & \text{if container } c \text{ is moved between} \\ & \text{GSI and ISA in hour } h; \\ 0, & \text{otherwise.} \end{cases}$$

Further define the following non negative integer variables:

t^i_h	number of RMG movements from GSI in hour $h \in H$
t^e_h	number of RMG movements to GSI in hour $h \in H$
t	$\geq \max_{h \in H}(t^i_h, t^e_h)$, i. e., maximum number of straddle operations in any hour.
v_h	total RMG operations in hour h. Direct exports count as two operations.
w_{hl}	number of RMG operations in excess of λ_l, $l \in L$.
p_h	amount of TEU resident in ISA at the end of hour $h \in H$.
q_{hm}	amount of TEU resident in ISA at the end of hour $h \in H$ in excess of μ_m, $m \in M$.

Constraints of the strategic IP

Each container has to be moved exactly once:

$$\sum_{h \in W_c} x_{ch} = 1 \quad \text{for all } c \in C$$

Count the GSI import and export operations per hour:

$$\sum_{c \in I} x_{ch} = t^i_h \quad \text{for all } h \in H$$
$$\sum_{c \in E} x_{ch} = t^e_h \quad \text{for all } h \in H$$

Compute the maximum number of straddle (GSI) operations needed in any hour. Assuming optimal pairing the number of straddle operations needed for a particular hour is the maximum of the number of import operations of any hour and the number of export operations of any hour:

$$t \geq t^i_h \quad \text{and} \quad t \geq t^e_h \quad \text{for all } h \in H \tag{1}$$

Constraints of the strategic IP

Determine the number of RMG operations (GRI+GSI) per hour :

$$v_h = |C_h| + t_h^i + t_h^e \quad \text{for all } h \in H$$

Compute the number of RMG operations exceeding level l:

$$w_{hl} = v_h - \lambda_l \quad \text{for all } h \in H, l \in L$$

Determine the number of containers resident in ISA at the end of the hour $h \in H$. On the GRI side, import containers in I_h leave the ISA whereas export containers in E_h enter the ISA. On the GSI side, the solution variables x_{ch} define the containers that are moved into or out of the ISA in hour h.

$$\begin{aligned} p_h &= p_{h-1} + \tau(E_h) - \tau(I_h) \\ &\quad - \sum_{c \in E} \tau_c x_{ch} + \sum_{c \in I} \tau_c x_{ch} \quad \text{for all } h \in H \end{aligned} \tag{2}$$

with $p_0 = 0$.
Compute the number of TEU resident in ISA at the end of hour h in excess of level m:

$$q_{hm} = p_h - \mu_m \quad \text{for all } h \in H, m \in M \tag{3}$$

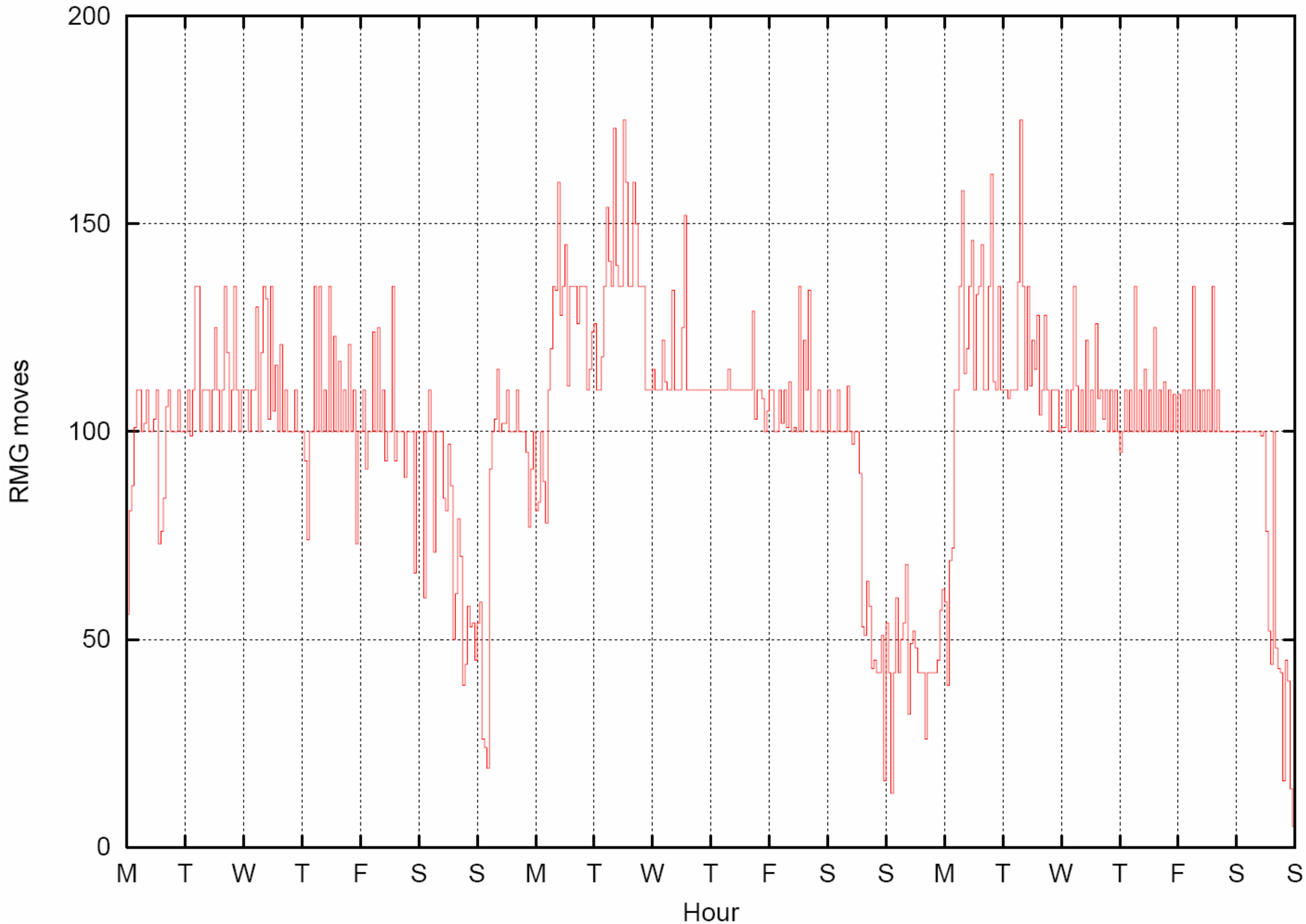
The IPs have typically about 350,000 variables, 50,000 constraints and 1 million non-zeros.
Solving time with CPLEX 10.0 is less than 5 minutes.

After solving the strategic IP:

- We have fixed for each individual container the hour of its GSI movement.
- Since the hour of its GRI movement is also fixed, we can now handle each hour independently.

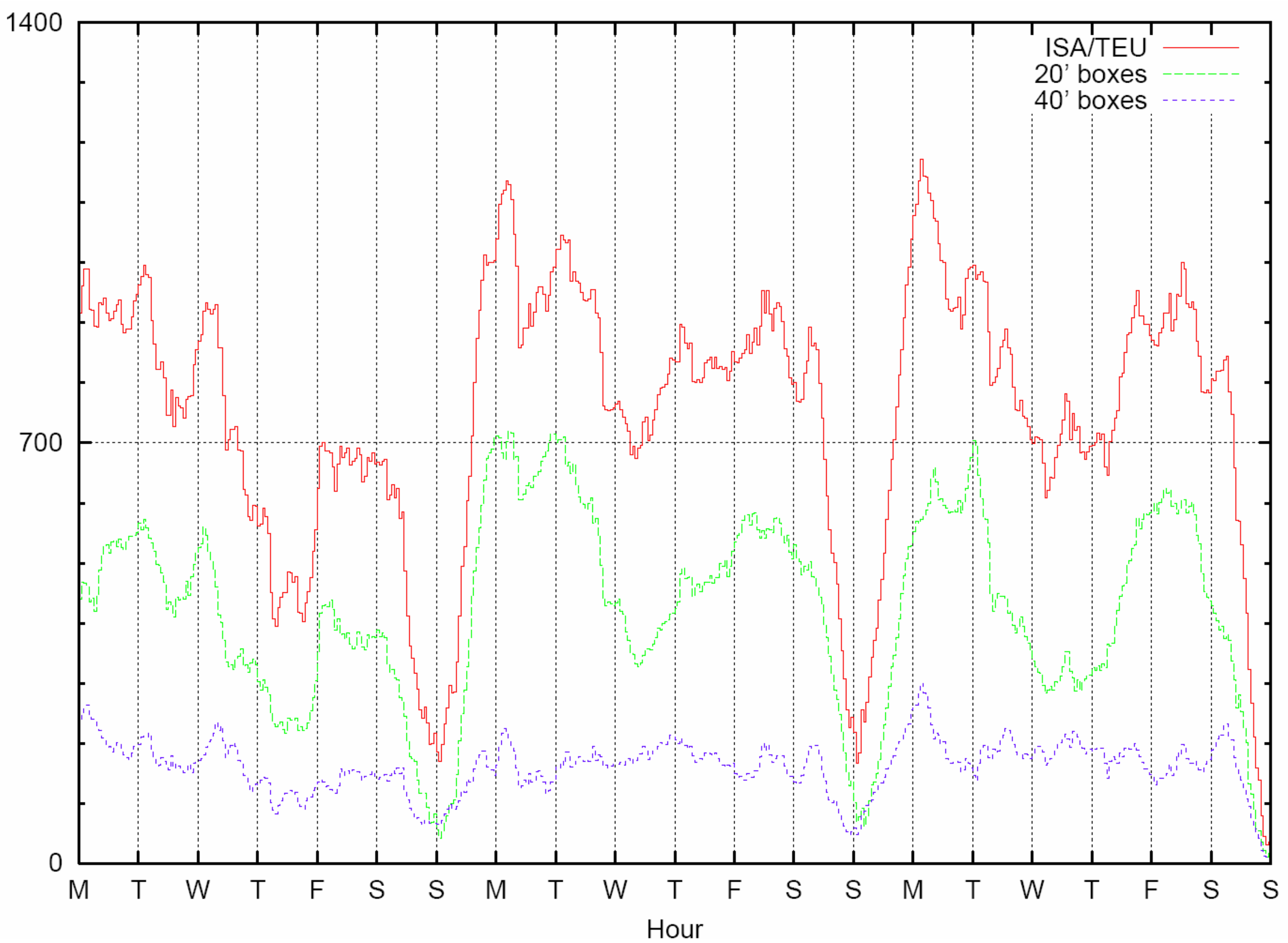
RMG operations per hour

Direct exports count as 2. Packing not counted.

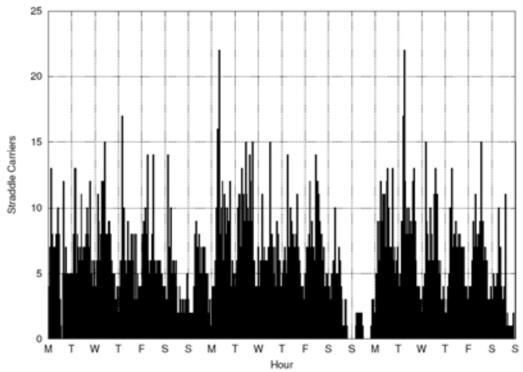


ISA utilization

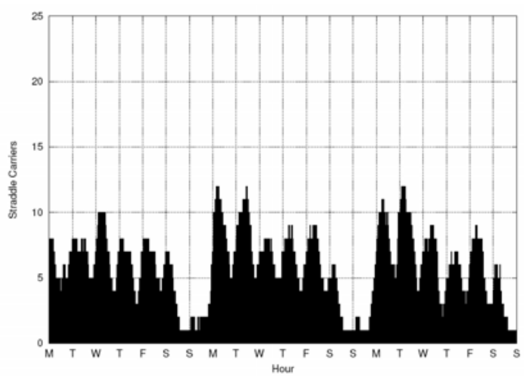
Max. capacity 2100 TEU



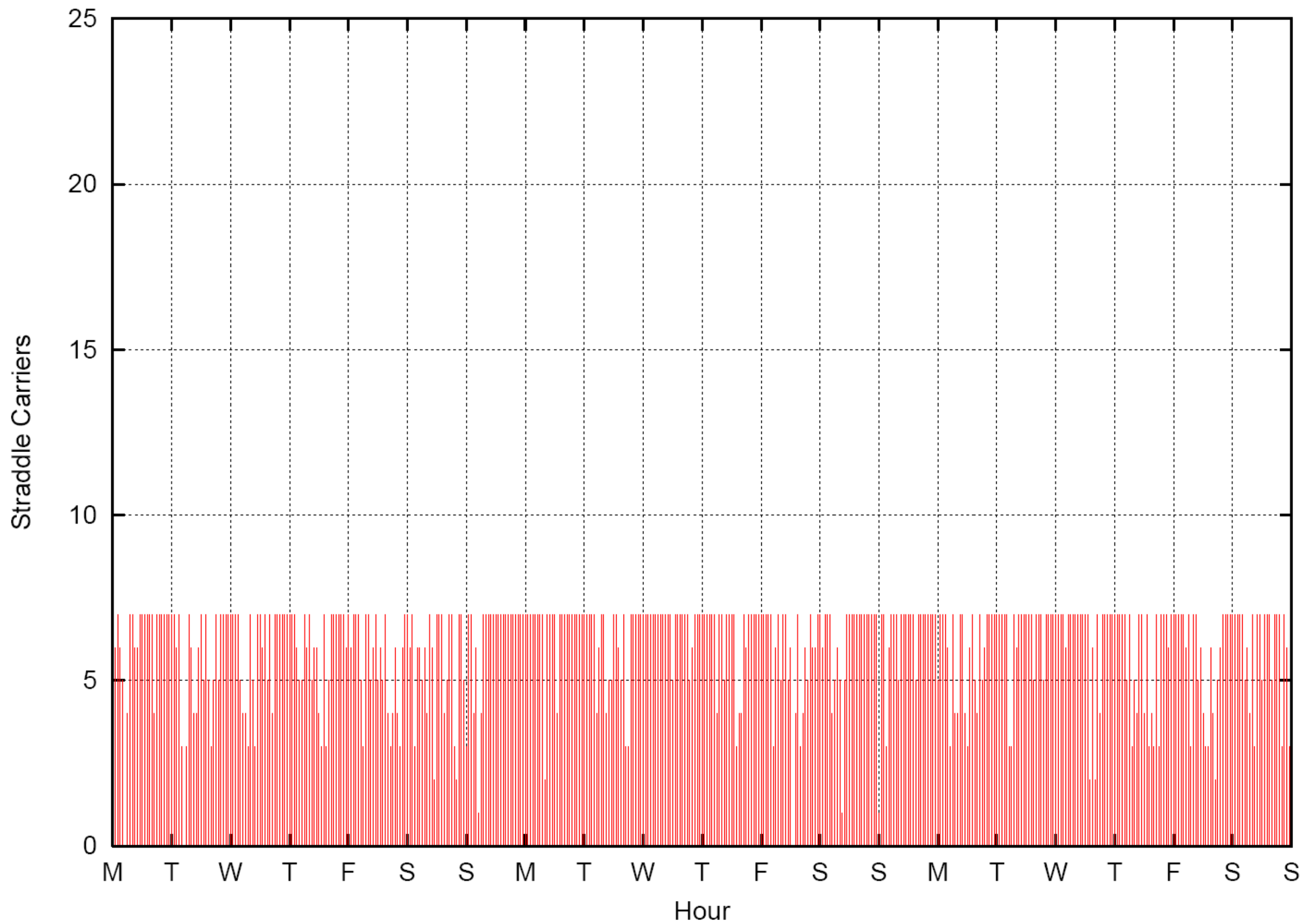
Number of Straddle Carriers needed



1 h average (22)

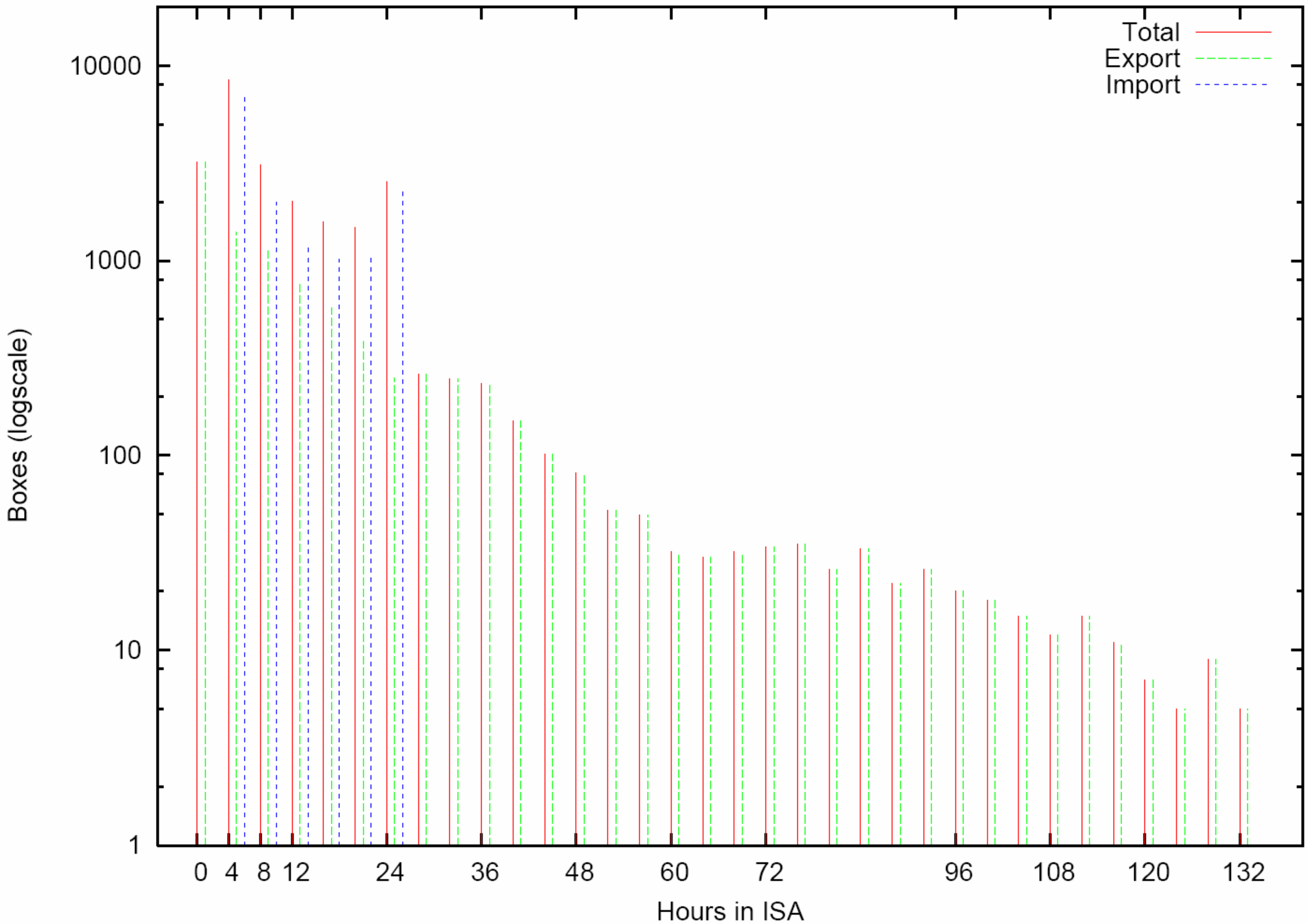


8 h average (12)



Strategic IP result (7)

Container dwell time in ISA



Tactical Setup: Distribution of Import Containers

Import containers have to be placed in the ISA before the GRI slot assignment for the trucks.

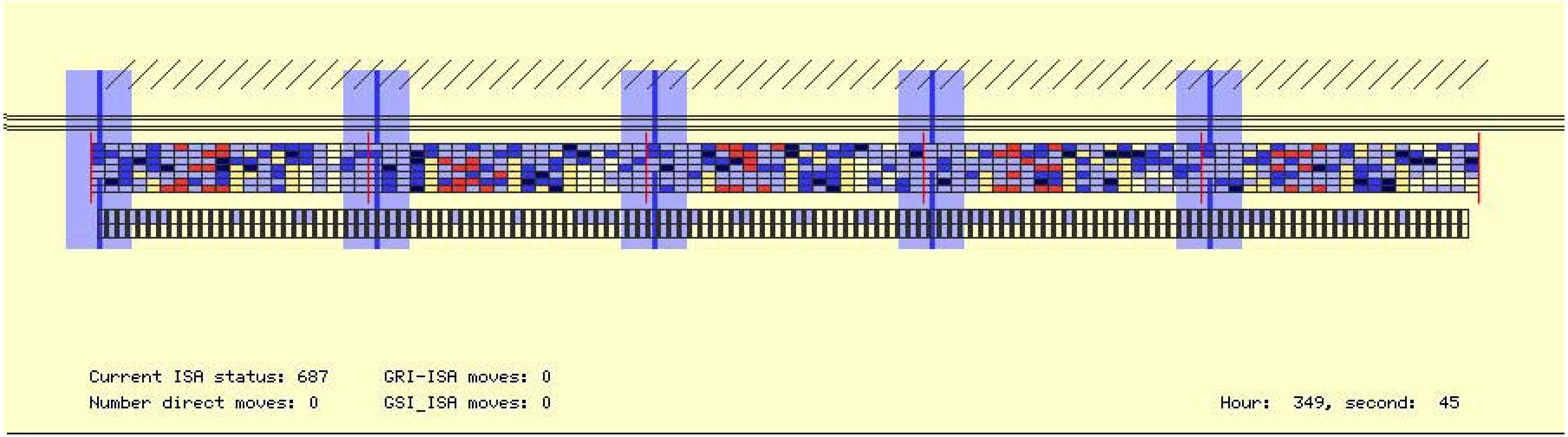
Goal: distribute evenly per RMG:

- Number of containers
- TEUs
- ISA dwelling time

This can be done, for example, by an integer program.

Operational Decision-making: Online Algorithm

The strategic planning has leveled the field to the point where a simple online algorithm can succeed.

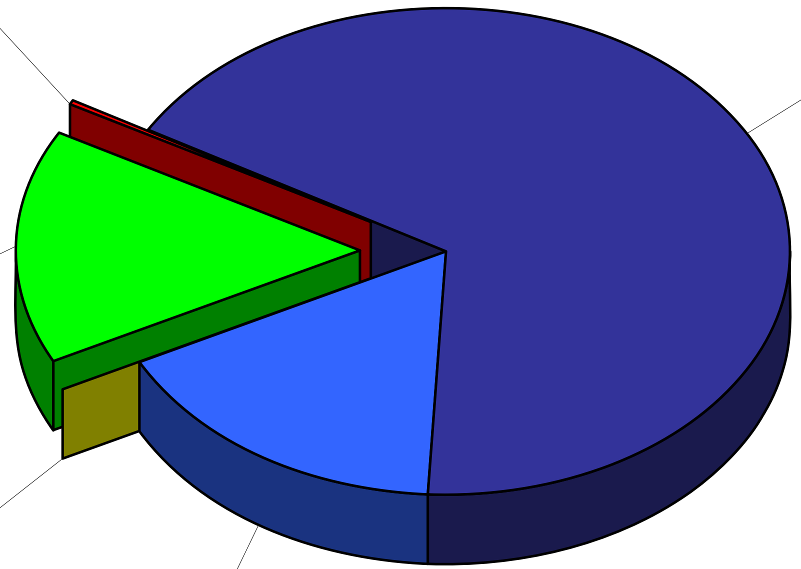


The Online Algorithm

1. Put all GSI↔ISA jobs into the "open" queue
2. If a truck arrives, construct a job and add it to the "admitted" queue
3. If the "admitted" queue is not empty
   Process next job from queue
   Goto 2
4. If "open" queue is not empty
   Is there a feasible job?
   Yes: select job and move it to the "admitted" queue
   No : If a pack operation is possible, put pack job into "admitted" queue
   Goto 2
5. If a nice pack job is possible, put pack job into "admitted" queue
   Goto 2

Whenever there is a choice, try to find something nearby.

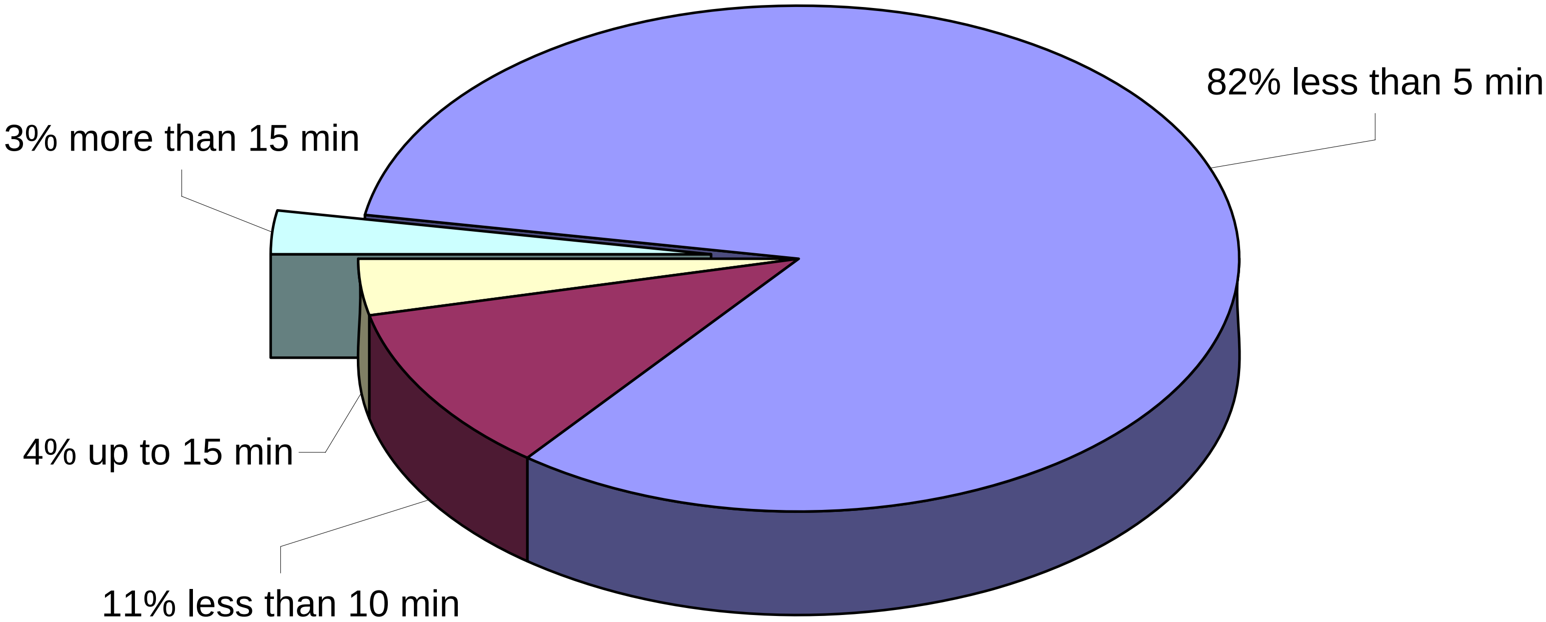
RMG Time Spend



RMG operation is within 8% of the optimum

- Load/unload operations and long travel are unavoidable
- Traveling under load is nearly optimal:
  only 0.1% of time exceeds time for long travel
- 15.4% of time are empty moves of which 7.9% are unavoidable
- 0.4% of time is used for packing containers

Truck waiting time



Reasons for excessive waiting times

Optimal movement:

No packing needed

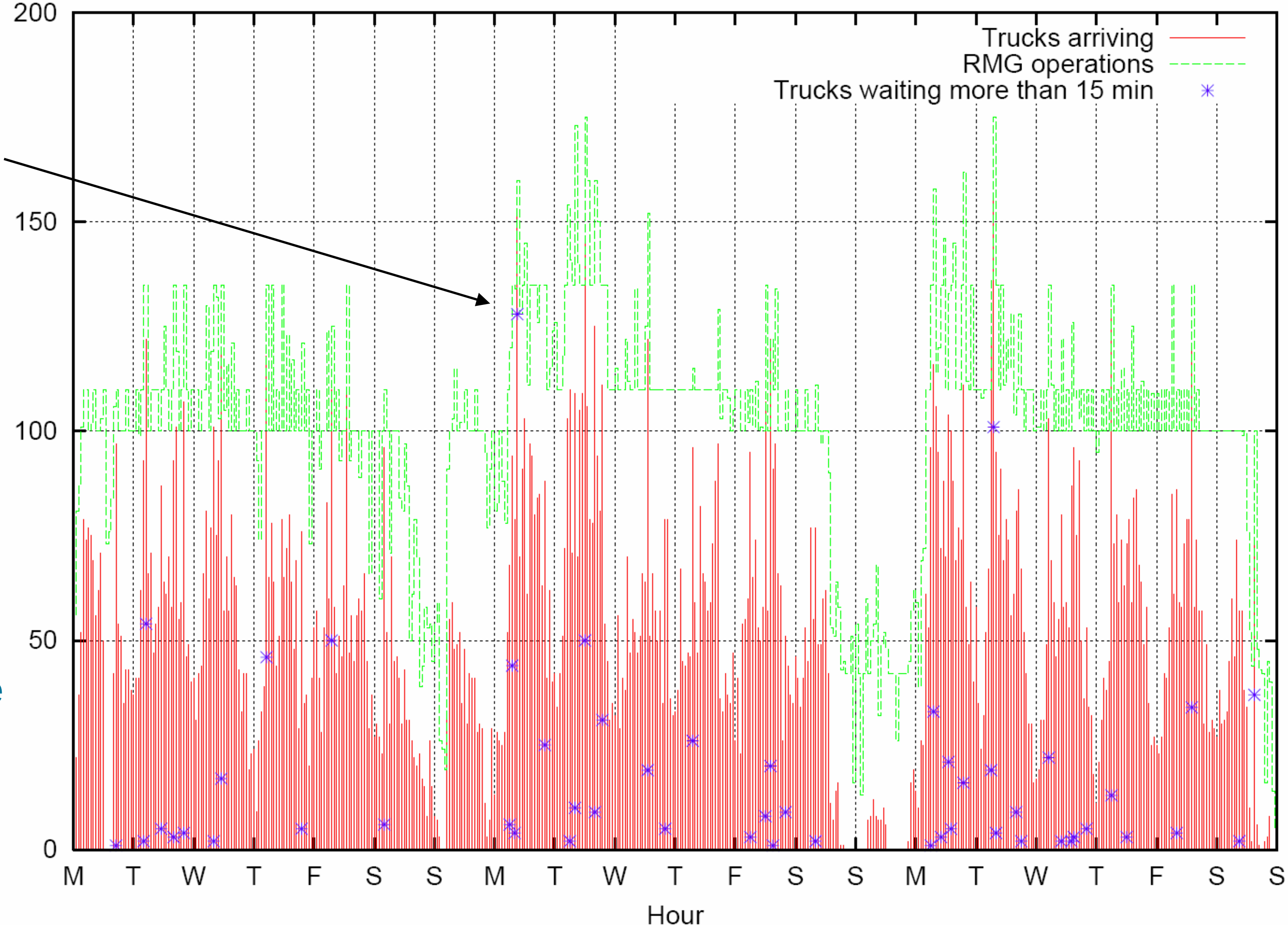
No cross travel time

But mainly import container:

- no choice of RMG

-Avg. move time
 135 s in this hour
 vs. 124 s overall
 vs. 110 s minimum

⇒Too much load!
 130 was achievable



Missing from the real world and the consequences

- Overload handling (will make things easier)
- Improve Online algorithm, esp. handle 40' containers precisely
- Trucks delivering/picking up more than one container
  (some things get more difficult some get easier)
- More theoretical insight into stacking is needed
- Incorporate trains (will make a difference)
- Incorporate truck handling (might make a difference)
- Special containers, like reefers, hold, X-ray, etc.
  (sometimes can be exported directly, capacity for reefers already checked, might decompose problem)
- Incorporating booking time windows for exports
  (IP will get much smaller, solution quality might suffer)
- Better GSI modeling including non uniform straddle availability

Conclusions

- The strategic IP works very well:
  It computes feasible schedules that are globally optimal.
  The global perspective ensures we do not paint ourselves in the corner.
- The Space-time Divisioning leads to very efficient RMG operations.
- The capacity of the ISA is heavily depending on the time needed for loading/unloading operations.

If the ISA is correctly dimensioned and intelligently controlled it allows top performance for the landside operation with minimum resource requirements.

Thank you!

Questions?