Sequencing: Optimal Scheduling of Activities Across Hierarchies of Management

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Introduction

- Large body of research on crew scheduling for tree harvesting but little on silvicultural scheduling
- Reforestation & plantation maintenance
  - Complex problem, need to coordinate multiple activities
  - Scheduling resources such as machinery and workers
  - Delivering planting stock, fertilizer, chemicals
  - Logistics of moving equipment, etc.

Plantation Establishment in Brazil

- Expanding forestry land base in southern Brazil
  - One client plans to increase plantations by 50 000 ha every year!
- Short rotations
  - 7 or 8 years, so delays in reforestation are costly
  - Plantations require regular maintenance to sustain productivity
- Workforce drawn from local towns
  - Various tasks, specialized skills (equipment operators) are limited
  - Workers commute via bus, company caters lunches
- Equipment is organized around UGOs
  - Associated with tree farms, but sometimes UGOs work elsewhere in nearby farms

A highly simplified example problem

- Decisions: assign equipment UGOs to plantations, allocate workers from nearby towns
- Monthly planning periods, 12-18 month planning horizon
- Objective: maximize area planted within time frame
- Constraints
  - Limited number of workers in each town, fixed daily work hours
  - Commuting time deducted from work time
    - Longer commutes to tree farms reduces daily production
  - UGO have same types of equipment but not same # of resources
  - All plantations must be planted
  - Plantations may require more than one month to complete

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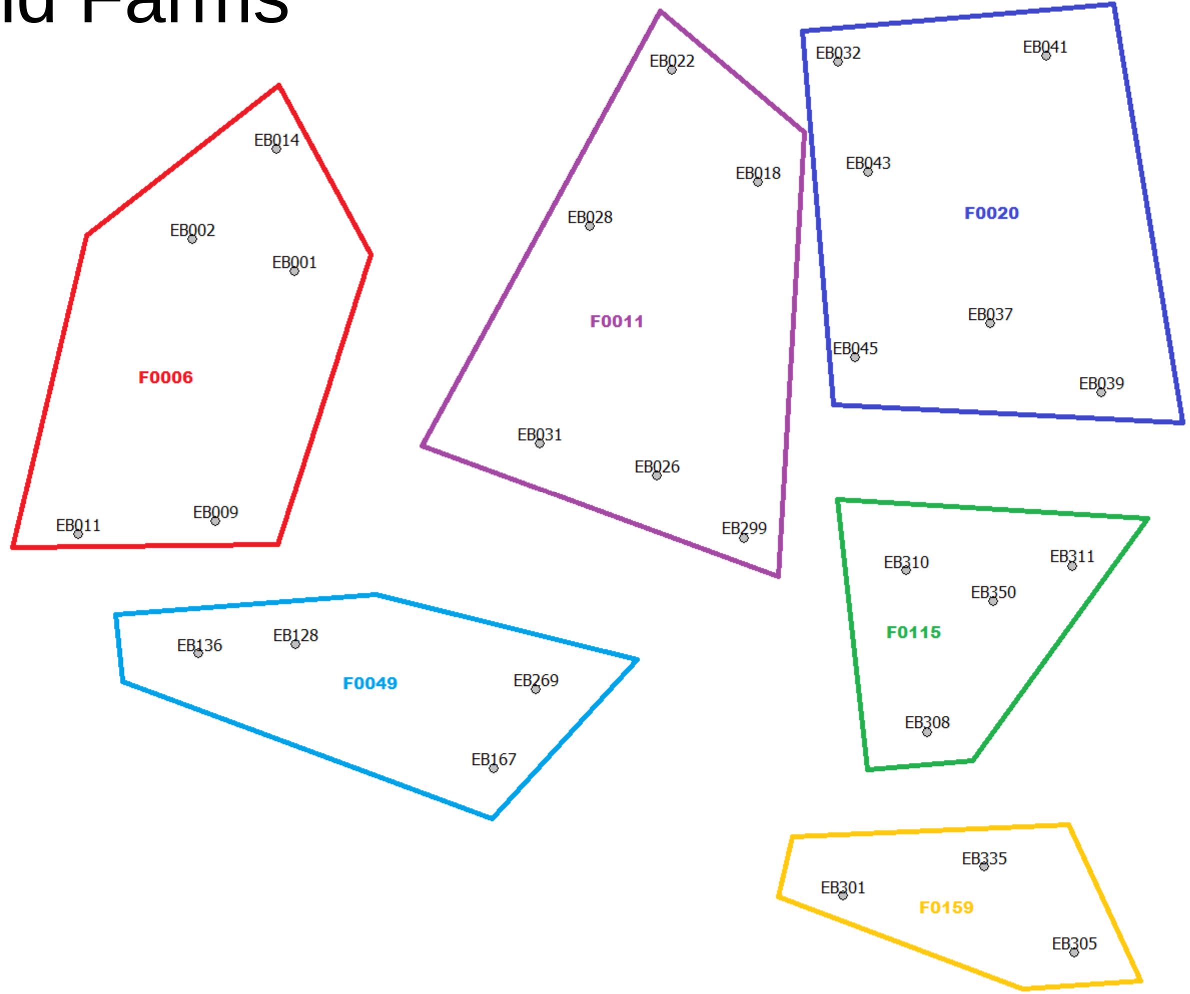
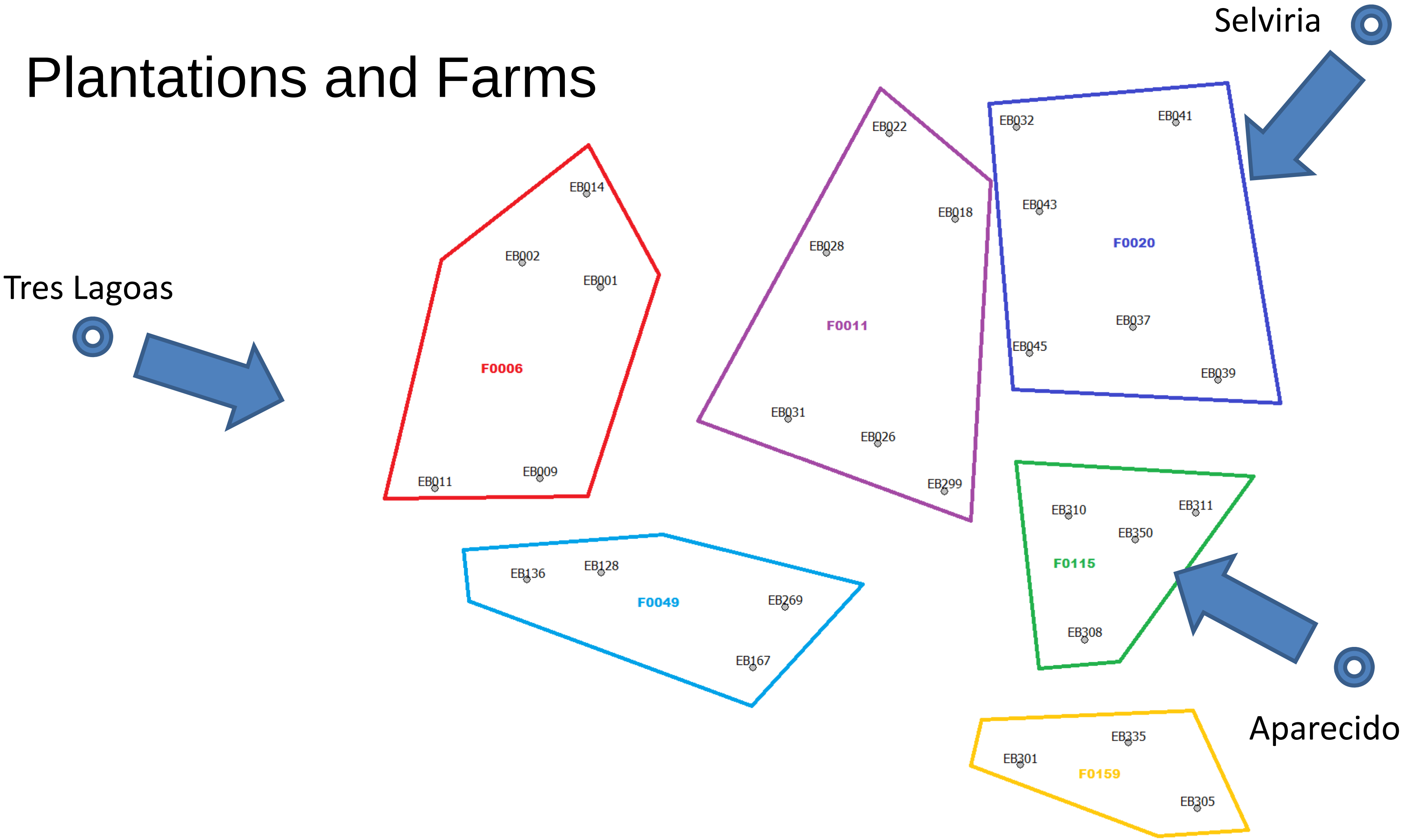
Plantations and Farms



Plantations and Farms



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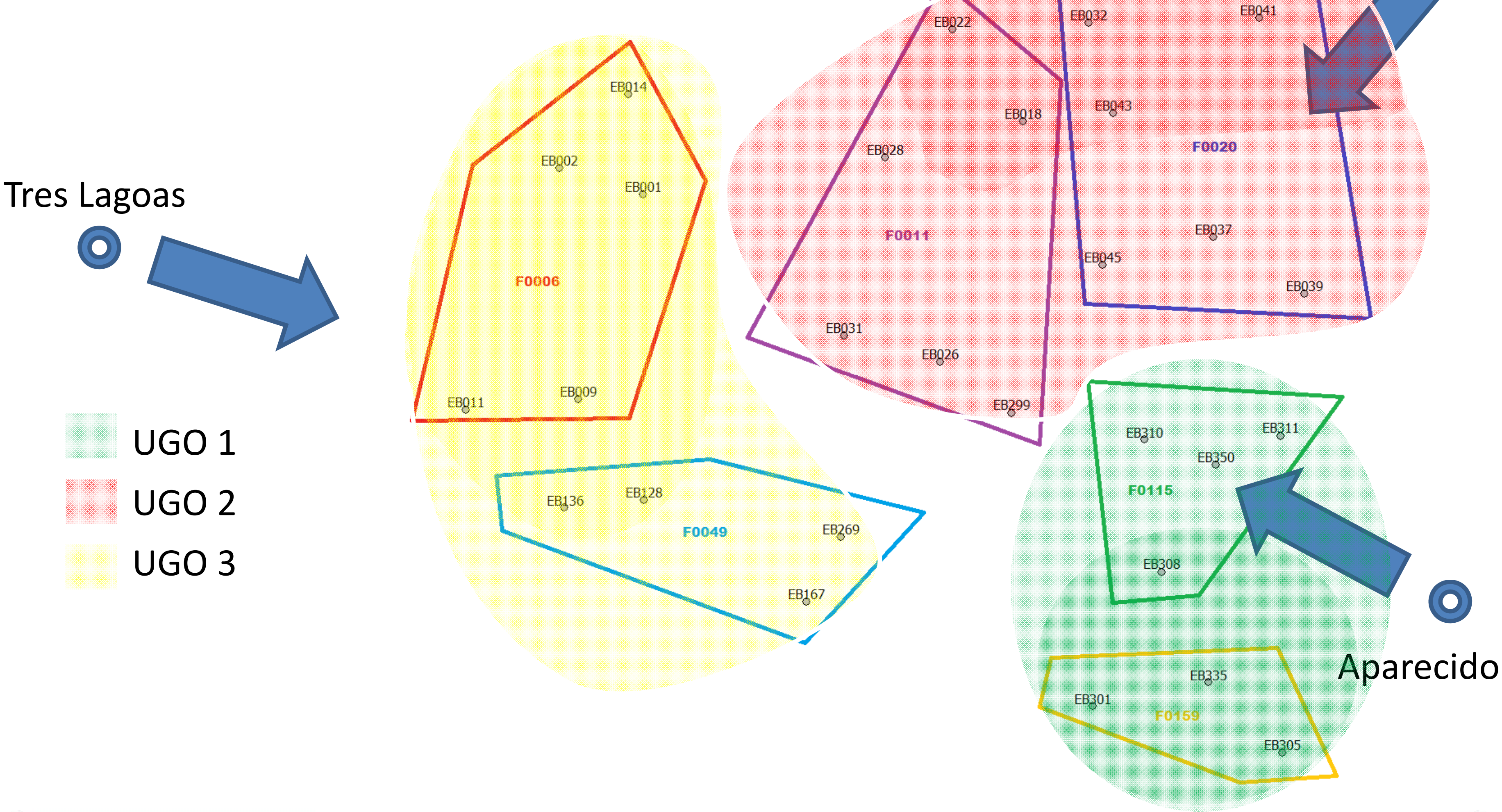
Plantations and Farms



Formulation

- Use a model I type of formulation for prescriptions
  - 1 decision variable = planting across multiple planning periods
  - Depending on size of plantation and productivity rates, prescriptions may span 2 or more planning periods
  - Binary decision variables (entire plantation must be planted)
- Need a way to quickly determine how long a job requires
  - Productivity rates are key to making this work
  - Can be as simple as ha/month, or could be equation taking into account terrain, seasonality, crew equipment etc.
  - Prescriptions can vary productivity across periods (start-up and float can reduce productivity.

Woodstock Syntax

- ```
  *REGIME rPlant
   *OPERABLE rPlant
     ? ? ? IMP ? OK ? N _AGE >= 1 ; afforestation
     ? ? ? REF ? OK ? N _AGE >= 1 ; reforestation
  ```

- ```
  *PRESCRIPTION rxPlant
        *OPERABLE ? ? ? ? ? OK ? N _AGE >= 1
        *TARGET ? ? ? MNT ? ? ? Y 100 _AGE 1
        _PERIODSTOCOMPLETE(yPrate,_BINARY)
         _RXPERIOD  _ACTION   _CAPACITY
             0       aPlant       100%; productivity can be <> 100%
             1       aPlant       100%
  ```

- ```
  *YC ? ? ? ? ? ? ? ?
  yPrate _EQUATION(yAerea / 750)
  ```
  ```

6 plantations, 3 tree farms, 1 UGO, 750ha/month

- *EB002 F0006 Selv Ref U2 A1 L0 N* 1 |Aaunit:F0006| 461.55 ha
  EB009 F0006 Selv Ref U2 A1 L0 N 1 |Aaunit:F0006| 318.47 ha
  EB018 F0011 Selv Ref U2 A1 L0 N 1 |Aaunit:F0011| 656.01 ha
  EB299 F0011 Selv Ref U2 A1 L0 N 1 |Aaunit:F0011| 347.07 ha
  EB041 F0020 Selv Ref U2 A1 L0 N 1 |Aaunit:F0020| 495.62 ha
  EB043 F0020 Selv Ref U2 A1 L0 N 1 |Aaunit:F0020| 438.93 ha
- B1 <= EB002
  B2 <= EB009, split into 288.45 (1), 30.02 (2)
  B3 <= EB018
  B4 <= EB299, split into 93.99 (1), 253.08 (2)
  B5 <= EB041
  B6 <= EB043, split into 254.38 (1), 184.55 (2)

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Algebraic formulation (MILP)

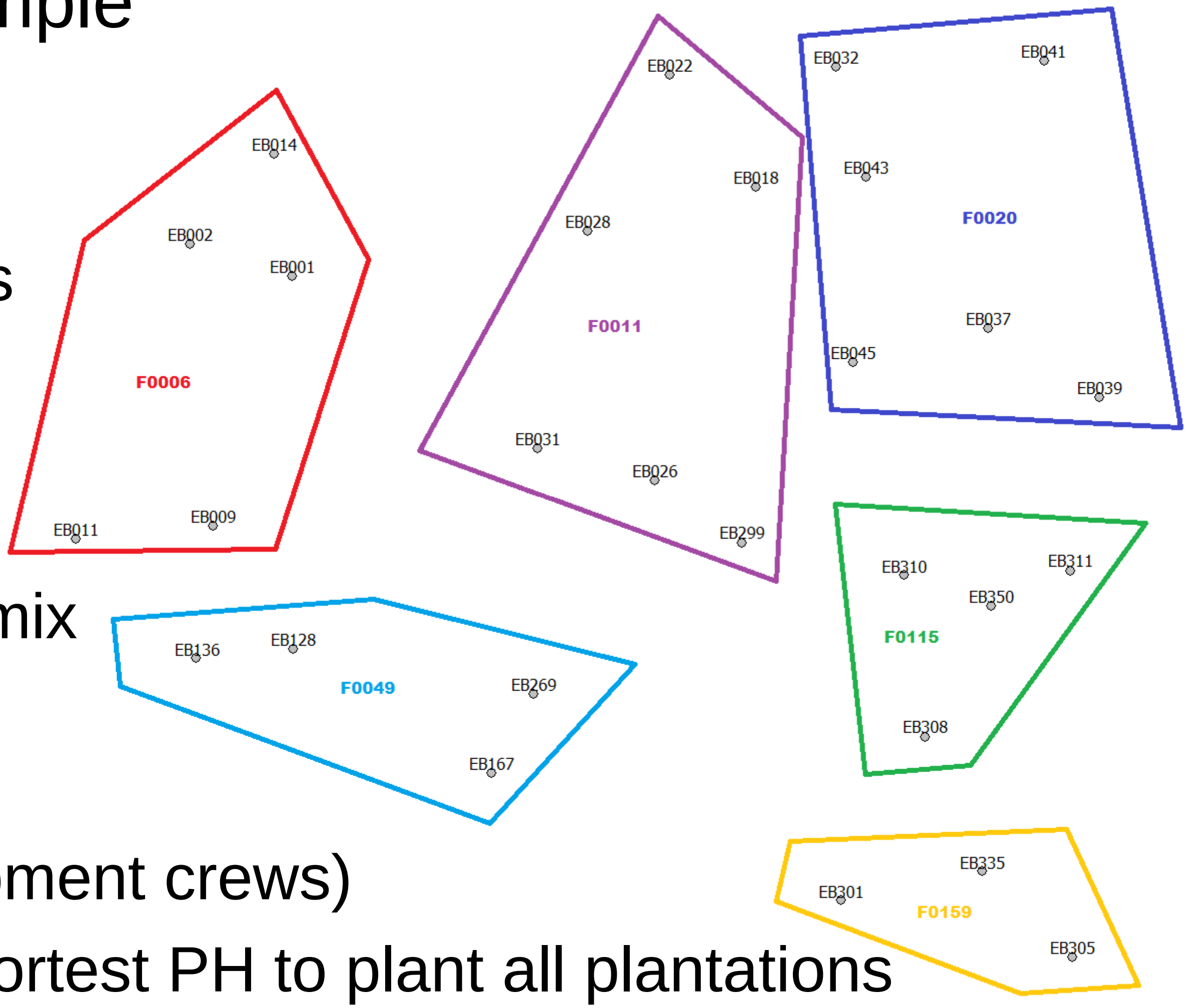
!Objective
MAX **OUT0000B**++**OUT0000C**+**OUT0000D**+**OUT0000E**
ST
! Initial Block Constraints
X1) **B1**+**B4**+**B7**+**B10**+**BU13** = 1
X2) **B2**+**B5**+**B8**+**B11**+**BU14** = 1
X3) **B3**+**B6**+**B9**+**B12**+**BU15** = 1
! Existing Stand Area Constraints
! Future Stand Area Transfer Rows (RU vars=completed plantations)
-B3 + **RU16** = 0
-B3 + **RU17** = 0
-B2 + **RU18** = 0
-B2 + **RU19** = 0
-B1 + **RU20** = 0
-B1 + **RU21** = 0
-B6 + **RU22** = 0
-B6 + **RU23** = 0
-B5 + **RU24** = 0
-B5 + **RU25** = 0
-B4 + **RU26** = 0
-B4 + **RU27** = 0
-B9 + **RU28** = 0
-B9-B12 + **RU29** = 0
-B8 + **RU30** = 0
-B8-B11 + **RU31** = 0
-B7 + **RU32** = 0
-B7-B10 + **RU33** = 0
0

! Accounting variables
+461.55B1 +288.449744B1 +656.01B2 +93.9898366B2 +384.07B3
+365.930123B3 **-OUT0000B** = 0 !*OAREF(A1)[1]*
+30.0202561**B1** +344.940163**B2** +129.689877**B3** +461.55**B4**
+288.449744**B4** +656.01**B5** +93.9898366**B5** +384.07**B6**
+365.930123B6 **-OUT0000C** = 0 *!OAREF(A1)[2*]
+30.0202561**B4** +344.940163**B5** +129.689877**B6** +461.55**B7**
+288.449744**B7** +656.01**B8** +93.9898366**B8** +384.07**B9**
+365.930123**B9** **-OUT0000D** = 0 !*OAREF(A1)[3]*
+30.0202561**B7** +344.940163**B8** +129.689877**B9** +461.55**B10**
+288.449744B10 +656.01**B11** +93.9898366**B11** +384.07**B12**
+365.930123B12 **-OUT0000E** = 0 *!OAREF(A1)[4*]

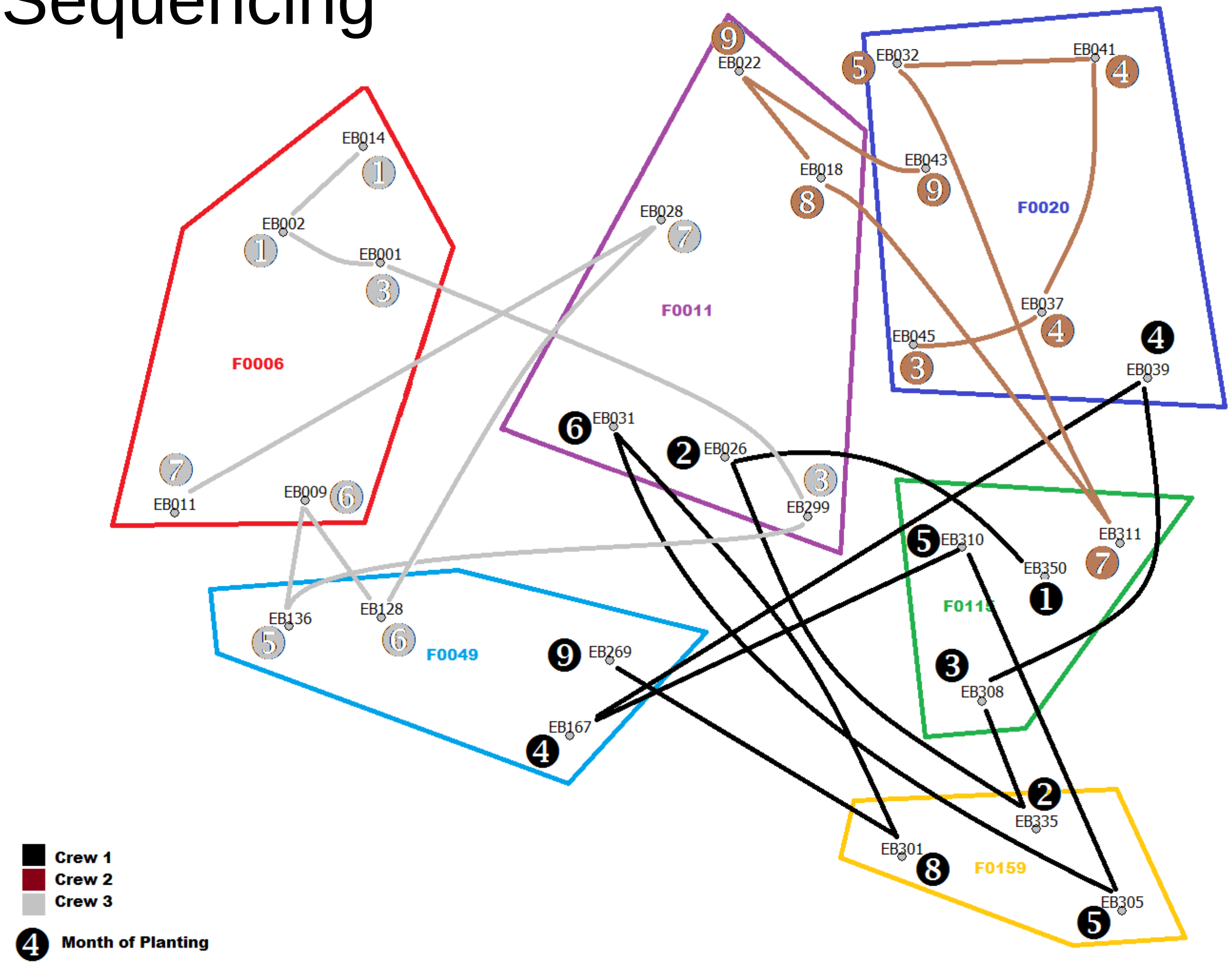
INTEGER **B1**
INTEGER **B2**
INTEGER **B3**
INTEGER **B4**
INTEGER **B5**
INTEGER **B6**
INTEGER **B7**
INTEGER **B8**
INTEGER **B9**
INTEGER **B10**
INTEGER **B11**
INTEGER **B12**

A Bigger Example

- 6 Tree Farms
- 28 Plantations
- Draw workers from 3 towns
- Each town has different mix of workers
- 750 ha/month
- 3 UGO (equipment crews)
- Determine shortest PH to plant all plantations



Plantation Sequencing



Formulation

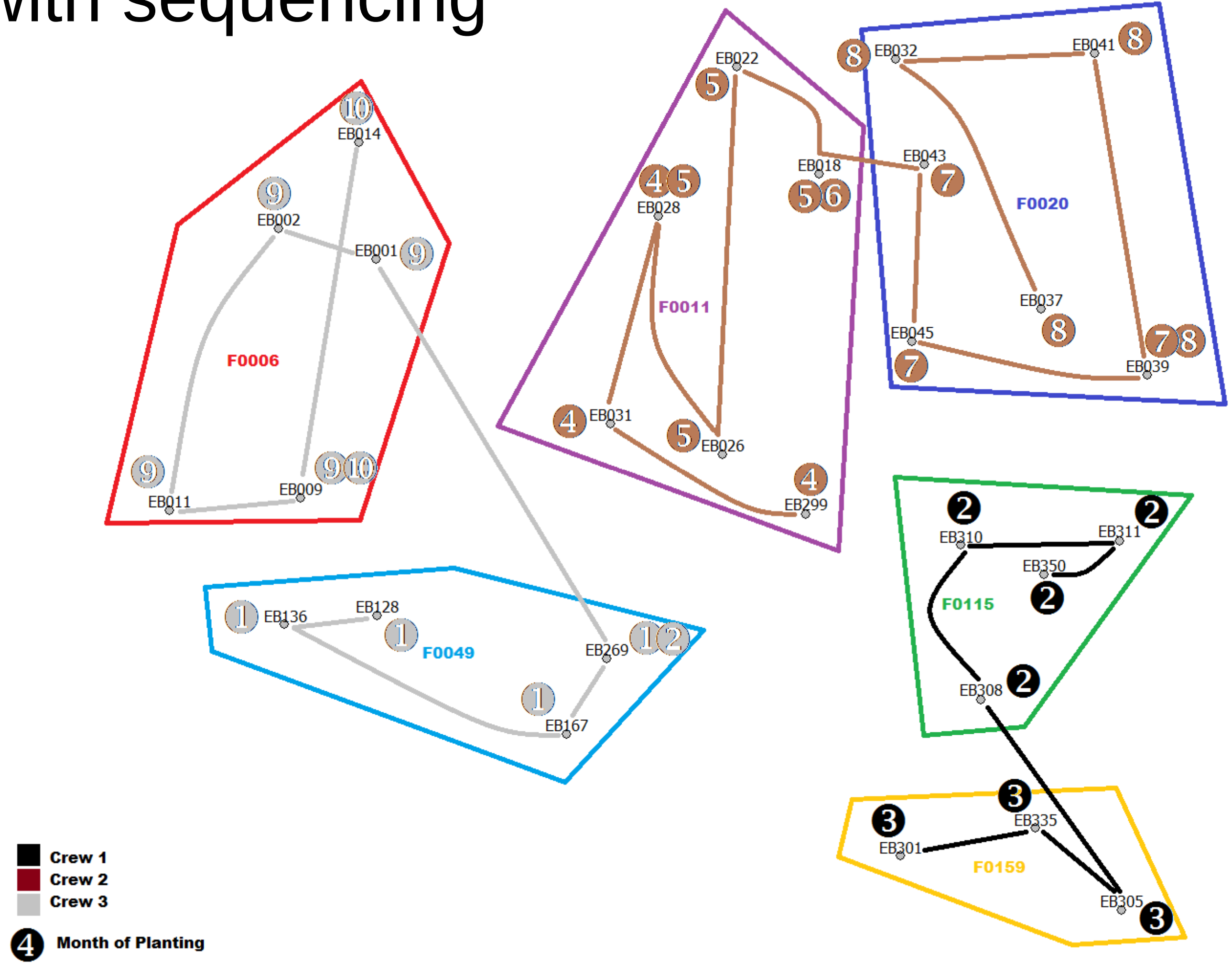
- Use a model I type of formulation for prescriptions
  - 1 decision variable = planting across multiple planning periods
  - Depending on size of plantation and productivity rates, prescriptions may span 2 or more planning periods
  - Binary decision variables (entire plantation must be planted)
- Use analysis area unit structure for tree farms
  - Planting prescriptions are linked together using analysis area units
  - Allocation of tree farms in a sequence forces plantations to be sequenced as well
  - Structurally the same as prescriptions but at higher order
  - Binary decision variables (no revisits to a farm)

Woodstock Syntax

```
*REGIME rPlant
 *OPERABLE rPlant
   ? ? ? IMP ? OK ? N _AGE >= 1 ; afforestation
   ? ? ? REF ? OK ? N _AGE >= 1 ; reforestation
*SEQUENCE _ASAP _TH2 _TH6 ; schedule by farm and UGO
*PRESCRIPTION rxPlant
    *OPERABLE ? ? ? ? ? OK ? N _AGE >= 1
    *TARGET ? ? ? MNT ? ? ? Y 100 _AGE 1
    _PERIODSTOCOMPLETE(yPrate,_BINARY)
     _RXPERIOD  _ACTION   _CAPACITY
         0        aPlant       90% ; productivity reduced 1st month
         1        aPlant       100%

*YC ? ? ? ? ? ? ? ?
YPrate _EQUATION(yAerea / 750)
*AACONTROL _KEEPAASGOING
```

Schedule with sequencing



Woodstock Syntax

```
*REGIME rPlant
 *OPERABLE rPlant
   ? ? ? IMP ? OK ? N _AGE >= 1 ; afforestation
   ? ? ? REF ? OK ? N _AGE >= 1 ; reforestation
*SEQUENCE _ASAP _TH2 _TH6 ; schedule by farm and UGO
   F0006 -> F0049 ; Farm 6 must be completed before Farm 49
*PRESCRIPTION rxPlant
    *OPERABLE ? ? ? ? ? OK ? N _AGE >= 1
    *TARGET ? ? ? MNT ? ? ? Y 100 _AGE 1
    _PERIODSTOCOMPLETE(yPrate,_BINARY)
     _RXPERIOD  _ACTION   _CAPACITY
         0        aPlant       90% ; productivity reduced 1st month
         1        aPlant       100%
*YC ? ? ? ? ? ? ? ?
yPrate _EQUATION(yAerea / 750)
*AACONTROL _KEEPAASGOING
```

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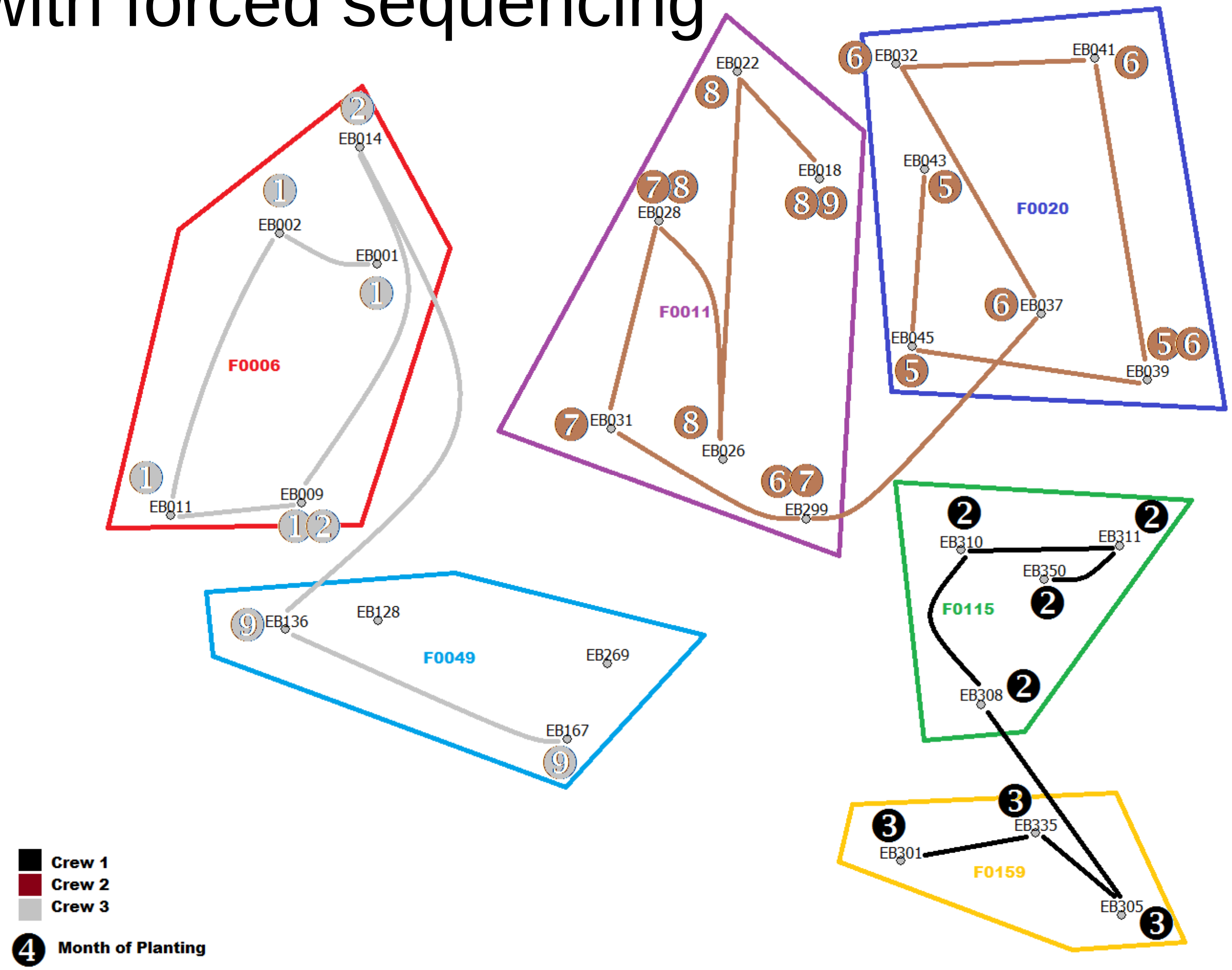
Schedule with forced sequencing



Real-world Example

- Minimize cost of planting, resources, buses
- ~800 plantations in about 270 farms
- 5 work types (laborer, foreman, operator, driver, tractor)
- 17 sources for workers but not all have every worker type or numbers of each worker type
- 6 UGOs for planting (3 manual, 3 mechanical)
- 50 constrained resources
- Seasonality restrictions on activities
- 18 month planning horizon

Real World Example

- *Model Size*
- *;* Matrix summary*
  ; Elapsed time = 0:01:46
  ; Columns = 225,622
  ; Rows = 94,247
  ; NonZeros = 2,297,237
  ; Filesize = 91,738,498
  ;

  ; Solver summary*
  ; Elapsed time for solver 13:36:38
- *5% gap*

Sum of Are	Mê										
3-fazenda	Set_14	Out_14	Nov_14	Fev_15	Mar_15	Abr_15	Mai_15	Jun_15	Jul_15	Dez_15	Totals
F0049											1.000
F0009											1.000
F0008											1.000
F0002											1.000
F0020											2.000
F0021											1.000
F0019											1.000
F0018											1.000
F0174											0.999
F2098											1.000
F2153											1.000
F2113											1.000
F0012											1.000
F0010											0.6750
Totals	4.000	2.000	3.000	0.3000	0.3000	0.3000	0.0990	1.000	2.000	1.675	14.67

Sum of Are	Mê												
3-fazenda	Set_14	Out_14	Nov_14	Dez_14	Jan_15	Fev_15	Mar_15	Abr_15	Mai_15	Jun_15	Jul_15	Dez_15	Totals
F0115													6.000
F0259													6.000
F0252													1.000
F0318													1.000
F0286													1.000
F0338													1.000
F0260													1.000
F0320													1.000
F2129													1.000
F2127													1.000
F2133													1.000
F2097													1.000
F2150													1.000
F2149													1.000
F2199													1.000
F2179													1.000
F2163													1.000
F1004													1.000
F0331													1.000
F0292												0.957	0.957
Totals	6.000	7.000	1.823	1.177	0.5250	1.475	2.000	2.000	2.000	2.000	2.000	1.957	29.96

Operational Scheduler in Continuing Development

- Currently used in operational harvest planning projects in several countries
- Right now limited to a single action within prescriptions
  - Representing all activities by same action in Woodstock doesn't capture precedence of some activities
  - Requires blended rates on some activities/costs
- Dependence on MILP formulations
  - Some model formulations solve very quickly yet others struggle to even find feasible solutions
  - More research into lifting constraints to help improve performance