Cellular Automaton Modeling of CFRP Component Production for Airframes

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1. Introduction:
   CFRP Airframe - Experimental / Mass Production

2. Cell Automaton:
   Lean Production - CFRP Components

3. Stagnation:
   Production Troubles in CFRP Components

4. Discussions

5. Concluding Remarks
Carbon Fiber Reinforced Plastics (CFRPs)

Experimental: Good!

Vacuum Assisted Resin Transfer Molding (VaRTM) CFRP Models: Experimental
CFRP Components: Supply Chain

- Supply Chain (Upper Stream)
- Prepreg Rolls: Cold Storage
- Prepreg Rolls: Warm Up (Tackness Recovery)
- Layup Machine: Setup/Operation
- Setup: Vacuum Bag/Linkage
- Green Body / Inventory
- Supply Chain (Lower Stream)
- CFRP Component
- Autoclave: Cure
- Co-Bond
CFRP Prepreg

Carbon Fibers + Resin

Shelf Life

- $-18^\circ$C: 6 Months
- Room Temperature: 2 Weeks
CFRP Components: Supply Chain

Supply Chain (Upper Stream)

6 Mon.

Prepreg Rolls: Washing (Tackness)

Prepreg Rolls: Curing

2 weeks

Setup: Vacuum Bag/Linkage

Laser Machine: Setup/Operation

Green Body / Inventory

CFRP Component

Autoclave: Cure

Co-Bond

Supply Chain (Lower Stream)
Carbon Fiber Reinforced Plastics (CFRPs)

Experimental: Good!

Vacuum Assisted Resin Transfer Molding (VaRTM) CFRP Models: Experimental
Boeing 787: Structural Materials

By Boeing.com

CFRPCs: ~50%

Steel 10%
Other 5%
Composite 50%
Titanium 15%
Aluminum 20%
Dates

2016: Target → 14/Mon.

Two Deliveries (2011, Sep. ~)

Monthly Delivery of Boeing 787
Learning Curve – ?

\[ \dot{N} = \dot{N}_{N=1} \times N^\alpha, \quad 0 < \alpha < 1 \cdots ? \]
Two Deliveries (2011, Sep.)

Monthly Delivery of Boeing 787

Dates

01-12-2011
01-04-2013
01-08-2014

2016: Target → 14/Mon.
Monthly Delivery of Boeing 787

Two Deliveries (2011, Sep.~)

2016: Target → 14/Mon.
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CFRP Components: Supply Chain

Supply Chain (Upper Stream)

Prepreg Rolls: Cold Storage

Prepreg Rolls: Warm Up (Tackness Recovery)

Layup Machine: Setup/Operation

Setup: Vacuum Bag/Linkage

Green Body / Inventory

Supply Chain (Lower Stream)

CFRP Component

Autoclave: Cure

Co-Bond
Supply Chain: Model

Supply Chain (Upper Stream)

Prepreg Rolls: Cold Storage

Prepreg Rolls: Warm Up (Tackness Recovery)

Layup Machine: Setup/Operation

Setup: Vacuum Bag/Linkage

Green Body / Inventory

CFRP Component

Autoclave: Cure

Co-Bond

Buffer Process

Buffer Process

Buffer Process

Buffer Process

Supply Chain (Lower Stream)
A Ring of Chain:

1, 2, 3, ••• n: ON

0 : OFF

<table>
<thead>
<tr>
<th>$P_i(0)$</th>
<th>$B_i(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$n$</td>
</tr>
</tbody>
</table>

$P_i(1)$ $B_i(n)$

$TP_i(0)$ $TB_i(n)$

$n$ inventories at buffer ••• Time
A Ring of Chain:

1, 2, 3 · · · n: ON

0: OFF

\[ P_i(0) \quad B_i(n) \]

\[
\begin{array}{c|c}
0 & n \\
\end{array}
\]

\[ TP_i(0) \quad TB_i(n) \]

\[ TP_i(1) \quad TB_i(n) \]

\[ P_i(1) \quad B_i(n) \]

\[
\begin{array}{c|c}
1 & n \\
\end{array}
\]

\( n \) inventories at buffer · · · Time
A Ring of Chain:

1, 2, 3 \cdots n: \text{ON}

0: \text{OFF}

\begin{align*}
\begin{array}{|c|c|}
\hline
P_i(1) & B_i(n) \\
\hline
1 & n \\
\hline
\end{array}
\end{align*}

\begin{align*}
\begin{array}{|c|c|}
\hline
P_i(0) & B_i(n) \\
\hline
0 & n \\
\hline
\end{array}
\end{align*}

\begin{align*}
\begin{array}{|c|c|}
\hline
TP_i(0) & TB_i(n) \\
\hline
\end{array}
\end{align*}

\begin{align*}
\begin{array}{|c|c|}
\hline
TP_i(1) & TB_i(n) \\
\hline
\end{array}
\end{align*}

n \text{ inventories at buffer} \cdots \text{Time}
A Ring of Chain:

1, 2, 3 \cdots \ n: \ ON

0 \quad \text{: OFF}

\begin{align*}
P_i(0) & \quad B_i(n) \\
0 & \quad n \\
\end{align*}

\begin{align*}
TP_i(0) & \quad TB_i(n) \\
TP_i(1) & \quad TB_i(n) \\
\end{align*}

\text{\(n\) inventories at buffer} \cdots \text{Time}
A Ring of Chain:

$1, 2, 3 \cdots n$: ON

$0$: OFF

$P_i(0)$ | $B_i(n)$
---|---
0 | $n$

$TP_i(0)$ | $TB_i(n)$

$n$ inventories at buffer

Time
A Ring of Chain:

1, 2, 3 • • • n: ON

0: OFF

\[ P_i(0) \quad B_i(n) \]

\[
\begin{align*}
P_i(1) & \quad B_i(n) \\
1 & \quad n
\end{align*}
\]

\[ TP_i(0) \quad TB_i(n) \]

\[ n \text{ inventories at buffer} \cdots \text{Time} \]
A Ring of Chain:

1: ON
0: OFF

\[
\begin{array}{cc}
P_i(1) & B_i(0) \\ 1 & 0 \\ \hline
TP_i(1) & TB_i(0) \\
\end{array}
\]

\[
\begin{array}{cc}
P_i(0) & B_i(0) \\ 0 & 0 \\ \hline
TP_i(0) & TB_i(0) \\
\end{array}
\]

Buffer \cdots "0"
Lean Production

Supplied Chain (Upper Stream)

1 or 0
Process
Prepreg Rolls: Cold Storage

1 or 0
Prepreg Rolls: Warm Up (Tackness Recovery)

1 or 0
Process
Layup Machine: Setup/Operation

1 or 0
Process

1 or 0
Setup: Vacuum/Greenlinkage

1 or 0
Process

1 or 0
Process

1 or 0
Process

1 or 0
Process

Supplied Chain (Lower Stream)

CFRP Component

Autoclave: Cure

Co-Bond

Green Body / Inventory
Lean Production

⇒ Cell Automaton: Wolfram Rule 184

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<tr>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
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<th>0</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>...</th>
</tr>
</thead>
</table>

**Time Step**

<table>
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<th>1</th>
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<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>...</th>
</tr>
</thead>
</table>

**Time Step**

<table>
<thead>
<tr>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>...</th>
</tr>
</thead>
</table>
Lean Production

⇒ Cell Automaton: ASEP Model

\[
\begin{array}{cccccccc}
0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \\
1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\
1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\
\end{array}
\]
Max. Throughput

- Cell Automaton: Wolfram Rule 184 -

\[ TR = \frac{1}{2} \sqrt{1 - 4p\rho(1 - \rho)} \]
Max. Throughput

- Cell Automaton: Wolfram Rule 184 -

*Work Density : 1/2*
Max. Throughput

- Cell Automaton: Wolfram Rule 184 -

\[ \text{Time Step} \]

\[ \text{Time Step} \]

\[ \text{Time Step} \]
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“IF” Over the Max. Throughput…?

- Cell Automaton: Wolfram Rule 184

```
... P=1 P=1 P=1 P=1 P=1 P=1 P=1 P=1 P=1 P=1 P=1 P=1 ...
1 1 1 1 1 1 1 1 1 1 1 1 1 ...
```

“Metastable” Condition
Over the Max. Throughput...?

- Cell Automaton: Wolfram Rule 184

"Metastable" Condition
Over the Max. Throughput…?

- Cell Automaton: Wolfram Rule 184

“Metastable” Condition
Over the Max. Throughput...?

- Cell Automaton: Wolfram Rule 184 -
Over the Max. Throughput…?

- Cell Automaton: Wolfram Rule 184 -
Over the Max. Throughput...?

- Cell Automaton: Wolfram Rule 184 -
Over the Max. Throughput...?

- Cell Automaton: Wolfram Rule 184 -
Over the Max. Throughput...?

“Slight Deviation → **Trigger** → Stagnation”

 CFRP: Shelf Life...

Line Stagnation
Accumulated Delivery of Boeing 787

Dates

Wingbox: 100th
Accumulated Delivery of Boeing 787

Wingbox: 100th
Accumulated Delivery of Boeing 787

![Graph showing accumulated delivery dates and Wingbox: 100th milestone.](image-url)
\[ \dot{N} = \dot{N}_{N=1} \cdot N^{0.515} \]
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CFRP Airframe Delivery

$N < 10 \sim 20$ Units / Month
Singe-Aisle Twin-Engine Liners

\[ N \sim 50 \text{ Units / Month} \]

If CFRPs... Production Lines:

B787/A350 × 3～4
Even Metal-based B737...
Single-Aisle Twin-Engine Liners

$N \sim 50$ Units / Month

CFRP?
Dreamlifter Operations Center (DOC)

“Buffer” for CFRP Wings

By Boeing Japan
Centennial Anniversary

Mitsubishi started airplane business in 1916 March at Kobe. MRJ is the great cornerstone toward a new century.

This picture was shot during the 10th MRJ flight, over Ontake and Fuji mountains with the South Japanese Alps on 4 March 2016.
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Concluding Remarks

CFRP Components: Difficult to Produce

Airframe : Mass Production

- Lean Production - Questionable
- Excessive Input – Stagnation / Low Delivery Rate

Present CFRPs of limited shelf life :

- Sub Components - Acceptable
- Main Components - Stagnation?

✓B737/A320 Class ⇒Metal + Limited CFRP Components