A stochastic programming approach for planning remanufacturing activities under uncertain returns and demand forecasts

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Journée du GDT COS
3 décembre 2015

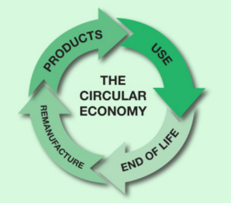
Plan

Plan

Circular economy

Linear industrial processes
"Take, Make, Dispose"
→ Depletion of natural resources
→ Waste generation and pollution

Circular industrial processes
End-of-life products = input to create new products



Reverse supply chains

- Transform end-of-life products returned by customers into once again usable products

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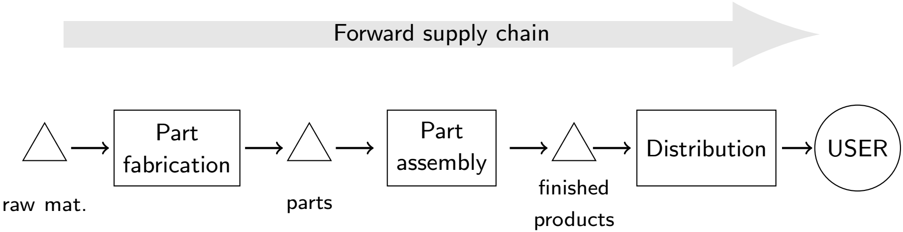
- Many activities:
  - collection,
  - transportation,
  - testing and sorting,
  - rehabilitation,
  - redistribution...

Rehabilitation activities



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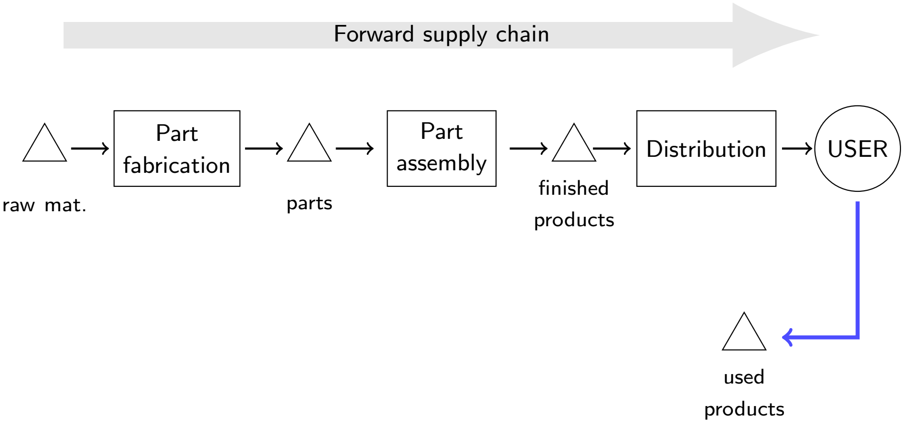

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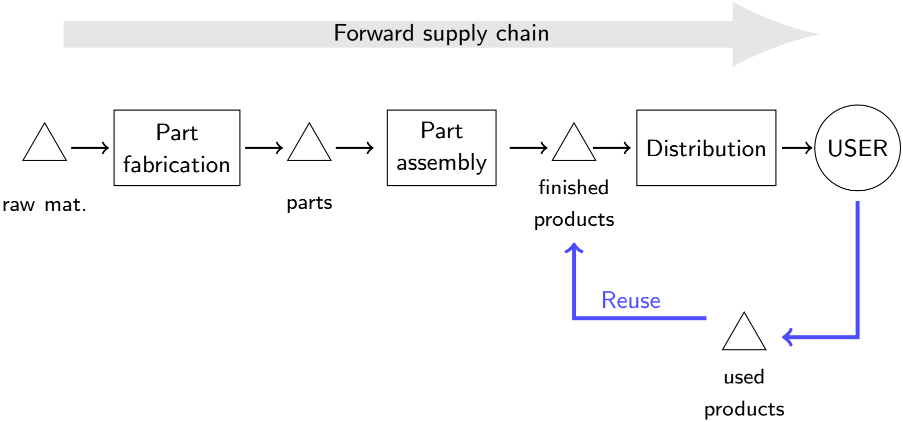

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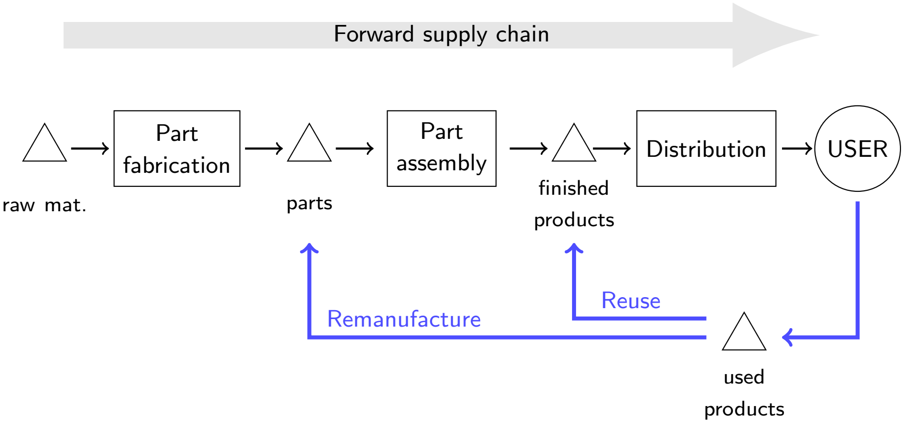

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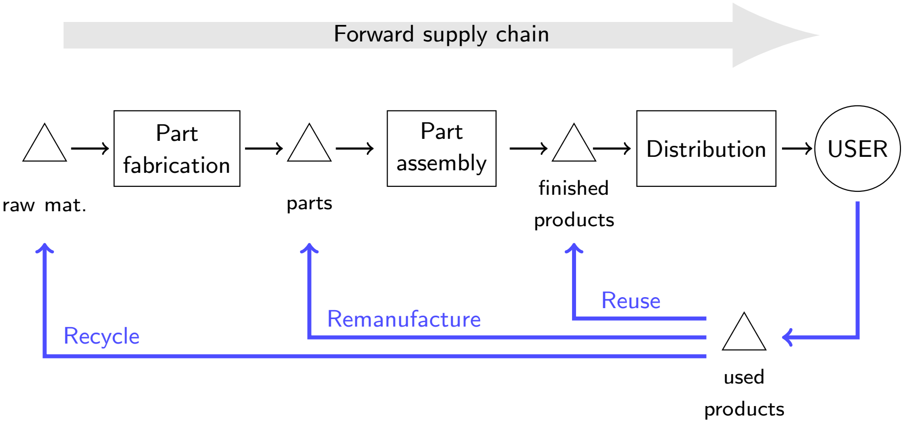

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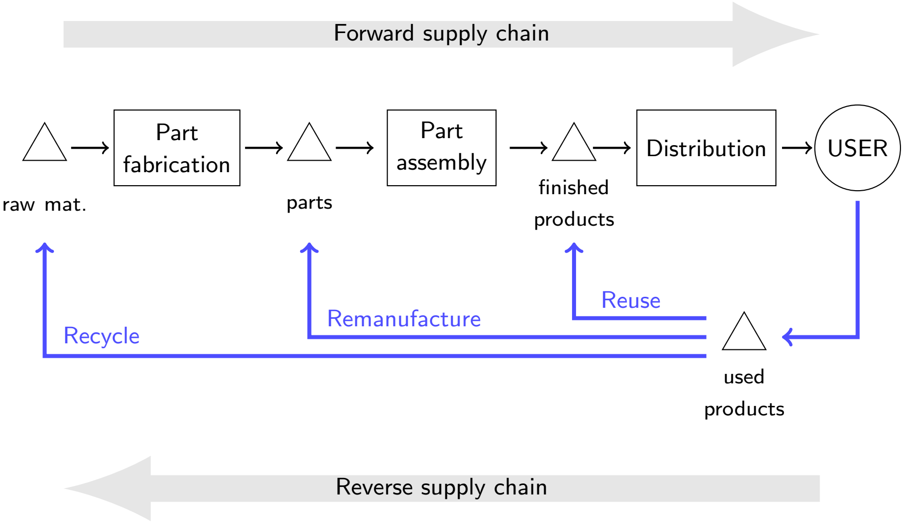

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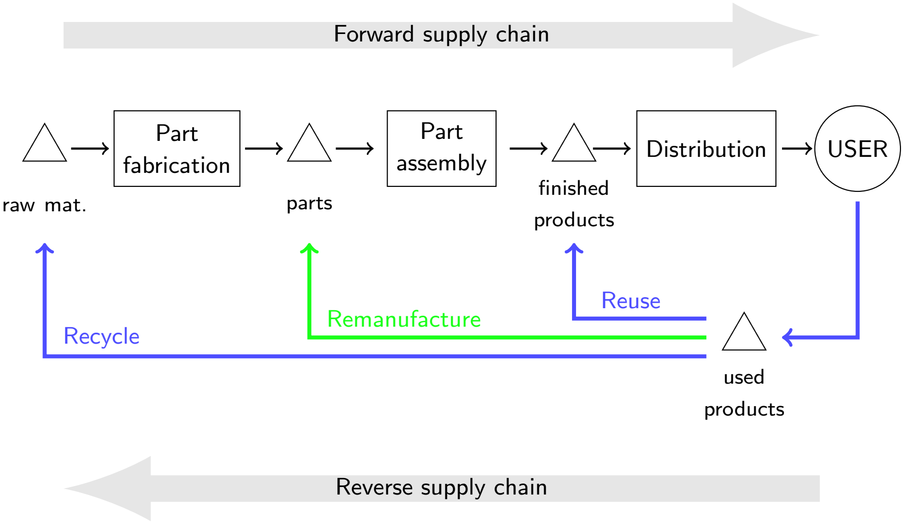
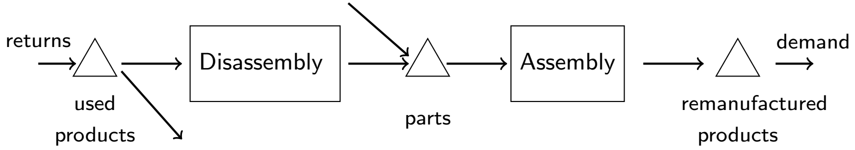


Remanufacturing planning

Remanufacturing system



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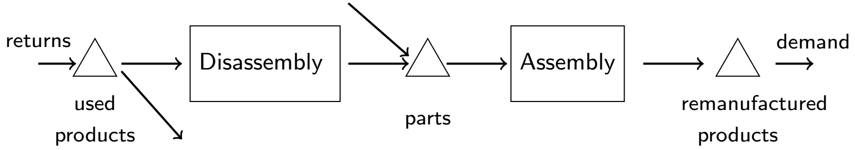

Aggregate production planning

Decide how many:

- used products to disassemble
- remanufactured products to assemble
- new parts to buy

Remanufacturing planning

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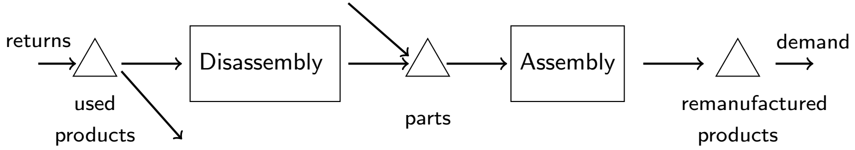

Aggregate production planning

Decide how many:

- used products to disassemble
- remanufactured products to assemble
- new parts to buy

so as to:

- satisfy customer demand
- respect technical constraints: capacity, bill of materials, inventory balance

while minimizing total remanufacturing costs.

Uncertain returns/demand

Uncertain returns

- A specific feature in reverse logistics
- End users $\neq$ suppliers
- Lack of control on product returns
- Uncertainty on returns quantity and quality

$\rightarrow$ Disorganization of the disassembly and assembly production plan

[Fleischmann *et al.*, 1997]

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[Fleischmann *et al.*, 1997]

Our proposal

A two-stage stochastic programming approach to take into account the uncertainty on:

- returns quantity / quality
- customer demand

Plan

Overview of the literature

Aggregate production planning for remanufacturing

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- General literature reviews
  [Aksali and Cetinkaya, 2011] , [Lage and Godinho, 2012]

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- Robust optimization problems
  [Wei *et al.*, 2011]

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Main current limitations

- Single product or single period planning problem
- Uncertainty on returns quantity or on returns quality

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Our proposal

Optimizing the planning of remanufacturing activities:

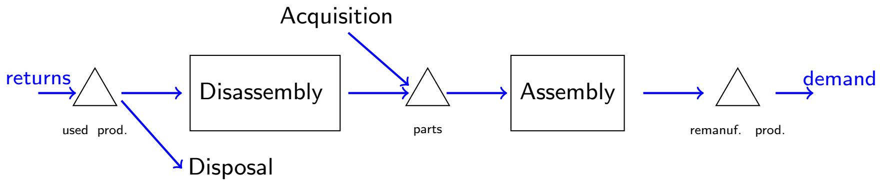
- for a multi-product multi-period setting
- with uncertainty on both returns quantity and quality

→ Two-stage stochastic programming approach

Plan

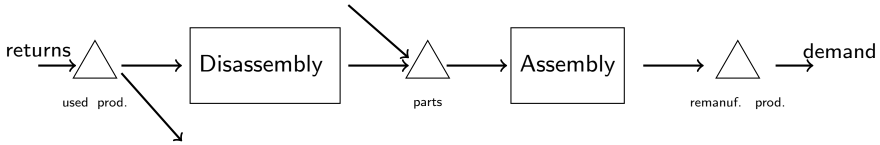
Problem description (1)

Product flows



Problem description (3)

Main decisions



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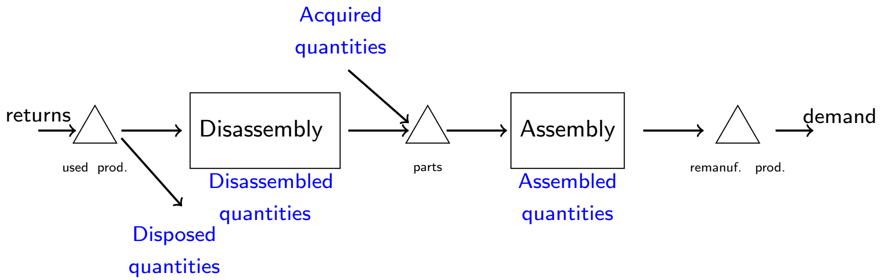

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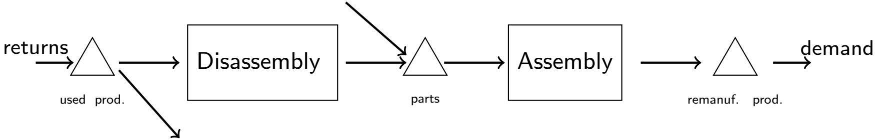

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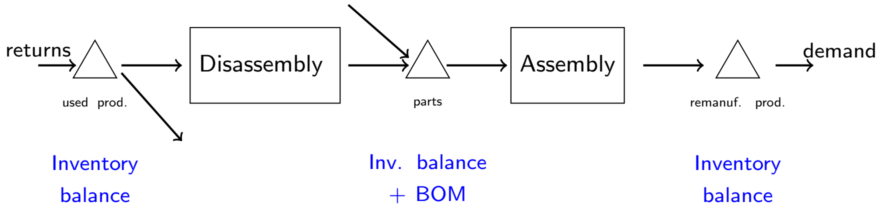

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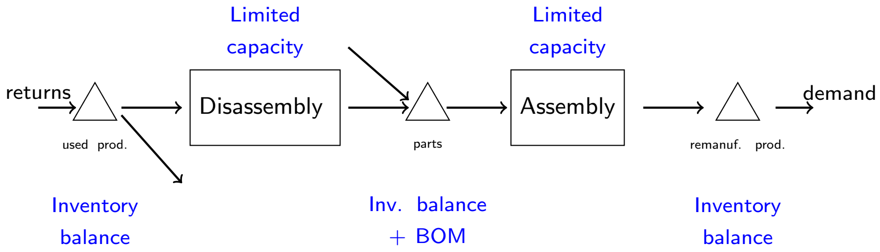

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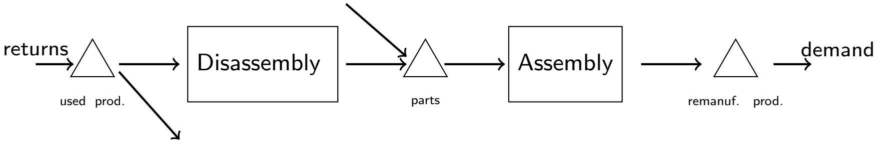
Costs



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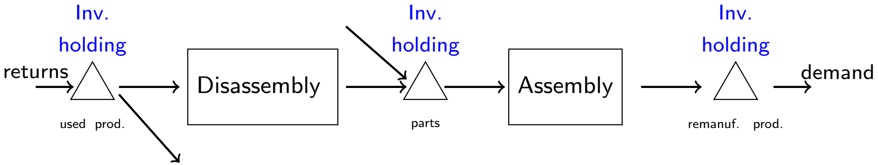

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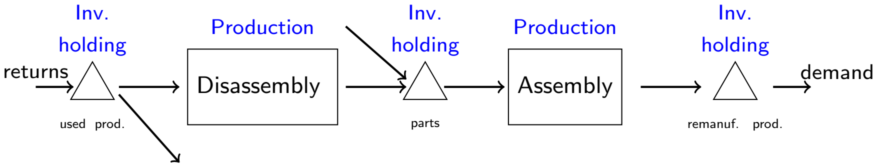

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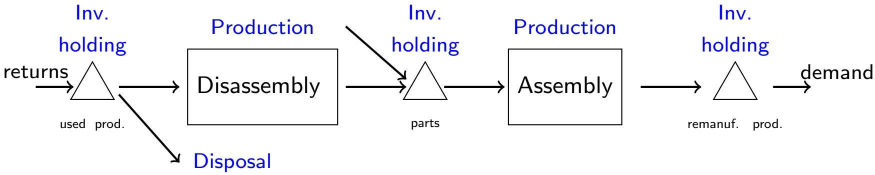

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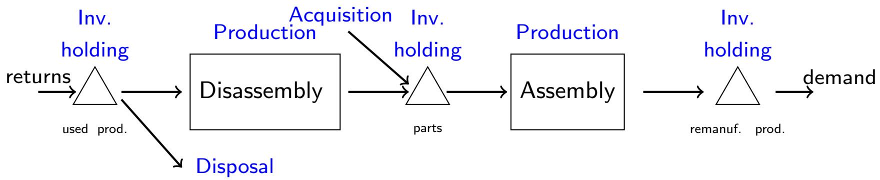

Problem description (5)

Quality of the returned products

Use of a finite set of discrete quality levels

For each returned product type and each quality level:

- A disassembly bill-of-material
- A per unit disassembly capacity consumption
- A per unit disassembly cost

[Jayaraman, 2006]

Assumption

The returned products have already been sorted and assigned to a quality level.

Linear programming formulation

$$Z^* = min \sum_{i,k,t} DC_{i,k,t} DQ_{i,k,t} + \sum_{i,t} RC_{i,t} RQ_{i,t} + \sum_{j,t} PC_{jt} PQ_{jt}$$
$$+ \sum_{i,k,t} DisC_{i,k,t} DisQ_{i,k,t} + \sum_{i,k,t} UIC_{i,k,t} UI_{i,k,t} + \sum_{j,t} MIC_{jt} MI_{jt} + \sum_{i,t} RIC_{i,t} RI_{i,t}$$

$$\sum_{i,k} DT_{i,k,t} DQ_{i,k,t} \leq DCap_t \qquad \forall t$$

$$\sum_{i} RT_{i,t} RQ_{i,t} \leq RCap_t \qquad \forall t$$

$$UI_{i,k,t} = UI_{i,k,t-1} + R_{i,k,t} - DQ_{i,k,t} - DisQ_{i,k,t} \qquad \forall i, \forall k, \forall t$$

$$MI_{j,t} = MI_{j,t-1} + \sum_{i,k} \pi_{i,k,j,t} \alpha_{i,j} DQ_{i,k,t} + MQ_{jt} - \sum_{i} \alpha_{i,j} RQ_{i,t} \qquad \forall i, \forall t$$

$$RI_{it} = RI_{i,t-1} + RQ_{i,t} - D_{it} \qquad \forall i, \forall t$$

Linear programming formulation

Production · Part acquisition

$$Z^* = min \underbrace{\sum_{i,k,t} DC_{i,k,t} DQ_{i,k,t} + \sum_{i,t} RC_{i,t} RQ_{i,t}}_{\text{Production}} + \underbrace{\sum_{j,t} PC_{jt} PQ_{jt}}_{\text{Part acquisition}}$$

$$+ \underbrace{\sum_{i,k,t} DisC_{i,k,t} DisQ_{i,k,t}}_{\text{Disposal}} + \underbrace{\sum_{i,k,t} UIC_{i,k,t} UI_{i,k,t} + \sum_{j,t} MIC_{jt} MI_{jt} + \sum_{i,t} RIC_{i,t} RI_{i,t}}_{\text{Inventory}}$$

Disposal · Inventory

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Capacity constraints

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Inventory balance constraints

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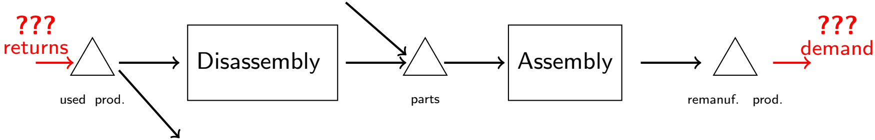
Plan

Uncertain returns/demand

Uncertain input data



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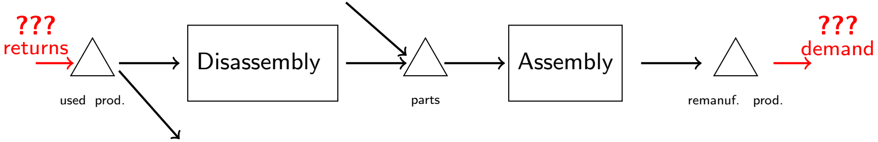

Practical consequences

- Demand
  → Impact limited to the remanufactured product inventory

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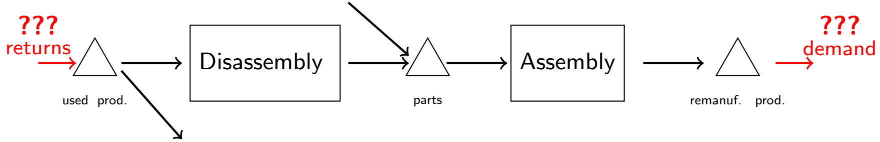

Practical consequences

- Demand
  → Impact limited to the remanufactured product inventory
- Returns quantity and quality
  → Disorganization of the disassembly and assembly production plan

Uncertain returns/demand

Modeling consequences

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$$UI_{i,k,t} = UI_{i,k,t-1} + \tilde{R}_{i,k,t} - DQ_{i,k,t} - DisQ_{i,k,t} \qquad \forall i, \forall k, \forall t$$

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Feasibility issues for the inventory balance constraints !

Uncertainty representation

Continuous random variables

- Uncertainty mostly due to forecasting errors
- Forecasting errors = Normally distributed random variables
- Terms involving integrals in the mathematical formulation
- $\rightarrow$ Computational difficulties

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A finite set of discrete scenarios

- Monte Carlo sampling of the continuous random variables $\tilde{R}_{i,k,t}$ and $\tilde{D}_{it}$
- A scenario s = a possible realization of all uncertain parameters
  - $R^s_{i,k,t}$: returned quantity for product (i,k) in t in scenario s
  - D^s_{it}: demand for product i in t in scenario s
- The larger the sample size, the better the approximation.

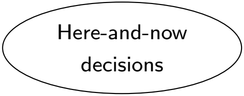
Two-stage stochastic programming approach

A two-stage decision process

Two-stage stochastic programming approach

A two-stage decision process

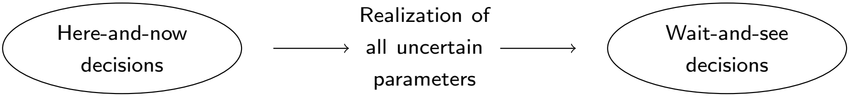
1. "Here-and-now" decisions
   Before the realization of the uncertain parameters
   Decisions common for all scenarios



Two-stage stochastic programming approach

A two-stage decision process

1. "Here-and-now" decisions
   Before the realization of the uncertain parameters
   Decisions common for all scenarios
2. "Wait-and-see" decisions / Recourse actions
   After the realization of the uncertain parameters
   Decisions specific to each scenario



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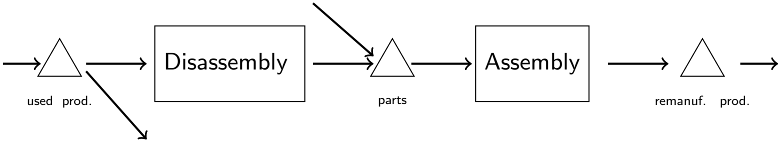
First stage decisions



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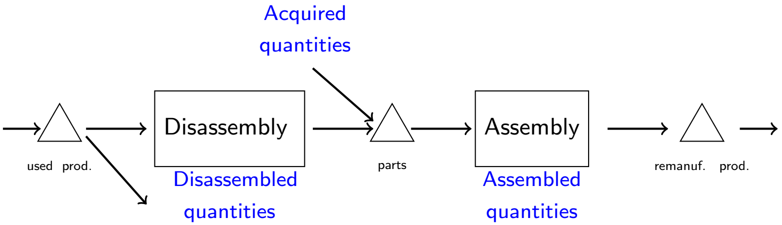
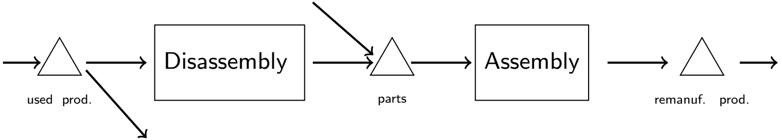


Two-stage stochastic programming approach

First stage constraints



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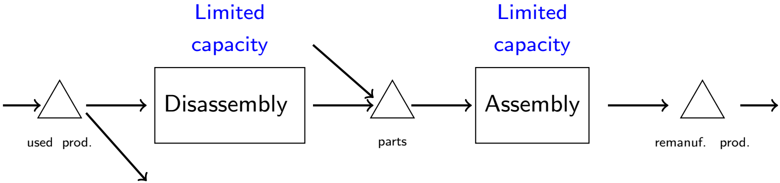
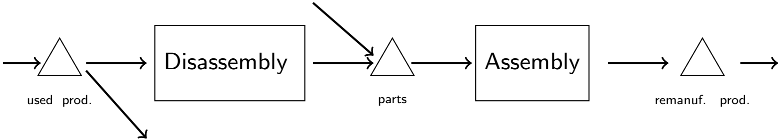


Two-stage stochastic programming approach

First stage costs



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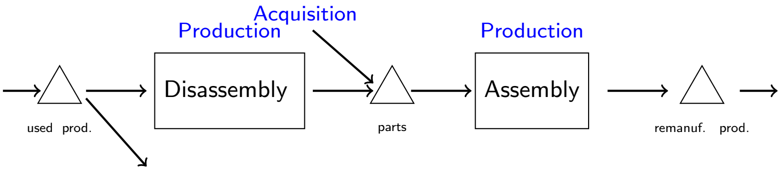
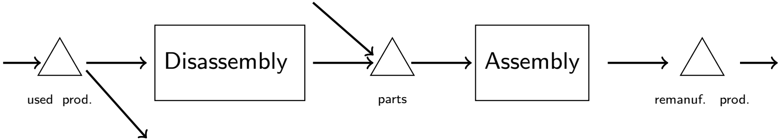


Two-stage stochastic programming approach

Second stage decisions



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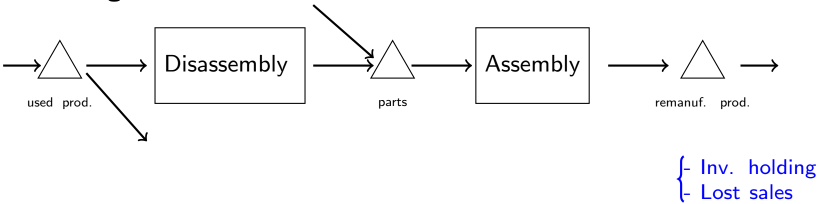

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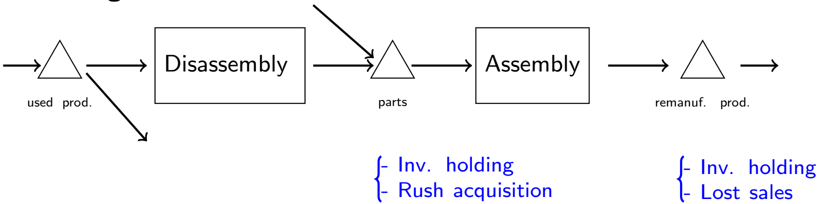

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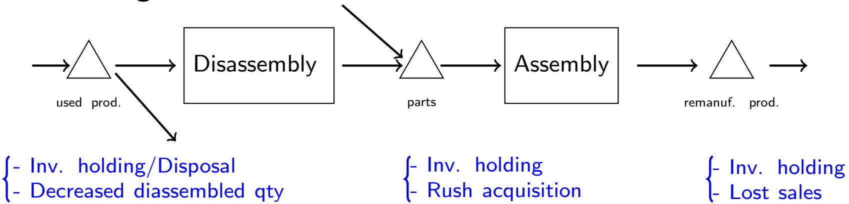

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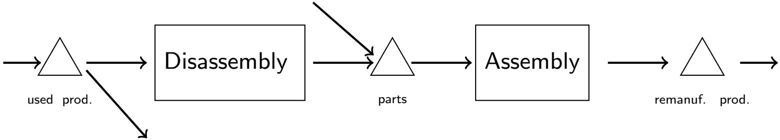

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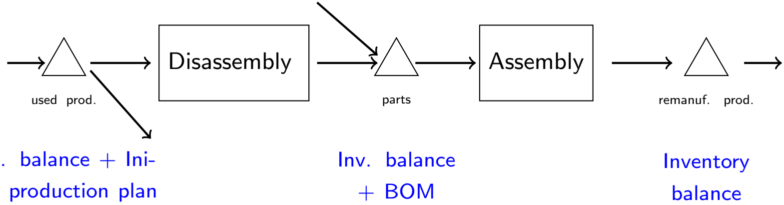

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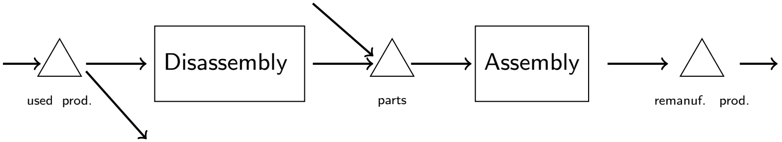
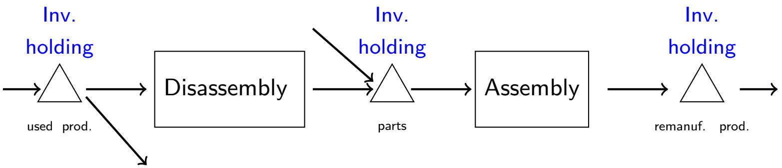
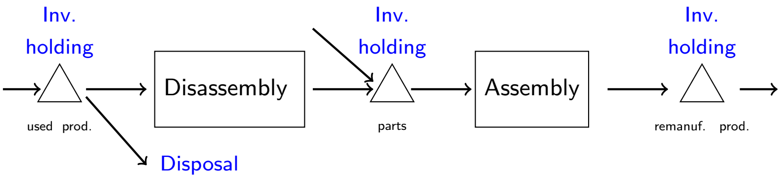


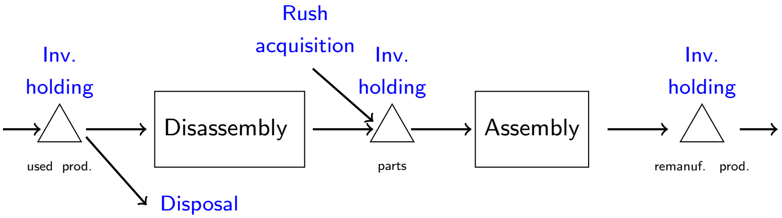
Second stage costs



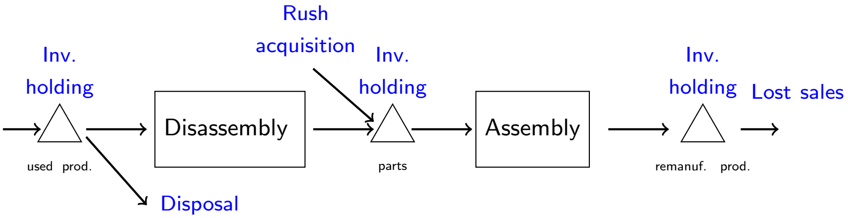
Second stage costs



Second stage costs



Second stage costs



Linear programming formulation

$$Z^* = min \sum_{i,k,t} DC_{i,k,t} DQ_{i,k,t} + \sum_{i,t} RC_{i,t} RQ_{i,t} + \sum_{j,t} MPC_{jt} MQ_{jt}$$
$$+ \sum_{s} \frac{1}{S} \Big[\sum_{i,k,t} DisC_{i,k,t} DisQ^s_{i,k,t} + \sum_{i,k,t} UIC_{i,k,t} UI^s_{i,k,t} + \sum_{j,t} MIC_{jt} MI^s_{j,t}$$
$$+ \sum_{jt} RMC_{jt} RMQ^s_{j,t} + \sum_{i,t} RIC_{i,t} RI^s_{i,t} + \sum_{i,t} LSC_{i,t} LS^s_{i,t} \Big]$$

$$\sum_{i,k} DT_{i,k,t} DQ_{i,k,t} \leq DCap_t \qquad \forall t$$

$$\sum_{i} RT_{i,t} RQ_{i,t} \leq RCap_t \qquad \forall t$$

$$UI^s_{i,k,t} = UI^s_{i,k,t-1} + R^s_{i,k,t} - modDQ^s_{i,k,t} - DisQ^s_{i,k,t} \qquad \forall i, \forall k, \forall t, \forall s$$

$$modDQ^s_{i,k,t} \leq DQ_{i,k,t} \qquad \forall i, \forall k, \forall t, \forall s$$

$$MI^s_{j,t} = MI^s_{j,t-1} + \sum_{i,k} \pi_{i,k,j,t} \alpha_{i,j} modDQ^s_{i,k,t}$$
$$+ MQ_{jt} + RMQ^s_{j,t} - \sum_{i} \alpha_{i,j} RQ_{i,t} \qquad \forall i, \forall t, \forall s$$

$$RI^s_{it} = RI^s_{i,t-1} + RQ_{i,t} + L^s_{i,t} - D^s_{it} \qquad \forall i, \forall t, \forall s$$

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First-stage costs

$$+ \sum_{s} \frac{1}{S} \Big[\sum_{i,k,t} DisC_{i,k,t} DisQ^s_{i,k,t} + \sum_{i,k,t} UIC_{i,k,t} UI^s_{i,k,t} + \sum_{j,t} MIC_{jt} MI^s_{j,t}$$
$$+ \sum_{jt} RMC_{jt} RMQ^s_{j,t} + \sum_{i,t} RIC_{i,t} RI^s_{i,t} + \sum_{i,t} LSC_{i,t} LS^s_{i,t} \Big]$$

Second-stage costs

$$\sum_{i,k} DT_{i,k,t} DQ_{i,k,t} \leq DCap_t \qquad \forall t$$

$$\sum_{i} RT_{i,t} RQ_{i,t} \leq RCap_t \qquad \forall t$$

$$UI^s_{i,k,t} = UI^s_{i,k,t-1} + R^s_{i,k,t} - modDQ^s_{i,k,t} - DisQ^s_{i,k,t} \qquad \forall i, \forall k, \forall t, \forall s$$

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$$+ \sum_{jt} RMC_{jt} RMQ^s_{j,t} + \sum_{i,t} RIC_{i,t} RI^s_{i,t} + \sum_{i,t} LSC_{i,t} LS^s_{i,t} \Big]$$

Second-stage costs

$$\sum_{i,k} DT_{i,k,t} DQ_{i,k,t} \leq DCap_t \quad \forall t$$
$$\sum_i RT_{i,t} RQ_{i,t} \leq RCap_t \quad \forall t$$

First-stage constraints

$$UI^s_{i,k,t} = UI^s_{i,k,t-1} + R^s_{i,k,t} - modDQ^s_{i,k,t} - DisQ^s_{i,k,t} \quad \forall i, \forall k, \forall t, \forall s$$
$$modDQ^s_{i,k,t} \leq DQ_{i,k,t} \quad \forall i, \forall k, \forall t, \forall s$$
$$MI^s_{j,t} = MI^s_{j,t-1} + \sum_{i,k} \pi_{i,k,j,t} \alpha_{i,j} modDQ^s_{i,k,t} + MQ_{jt} + RMQ^s_{j,t} - \sum_i \alpha_{i,j} RQ_{i,t} \quad \forall i, \forall t, \forall s$$
$$RI^s_{it} = RI^s_{i,t-1} + RQ_{i,t} + L^s_{i,t} - D^s_{it} \quad \forall i, \forall t, \forall s$$

Second-stage constraints

Plan

Instances

Instance size

	Used/remanuf. products	Quality levels	Parts	Periods
Instance 1	2	6	2	2

Numerical values of the deterministic parameters

Case study presented in [Jayaraman, 2006]

Remanufacturing of mobile phones

Scenario generation

- Random parameters: Normal distribution $\mathcal{N}(\mu, \sigma)$
- μ: case study presented in [Jayaraman, 2006]
- σ: 0.1μ or 0.2μ

Preliminary results

Computational difficulty

Results for $\sigma = 0.1\mu$

Scenarios	Variables	Constraints	Cost	Std dev.	Comp. time
1	120	60	89160	_	0.05s
10	912	564	96047	1355	0.05s
100	8832	5604	98810	534	0.30s
1000	88032	56004	98860	149	7.05s
2000	176032	112004	98970	71	19.1s
5000	440032	280004	98898	69	70.9s
10000	880032	560004	_	_	_

- Resolution with CPLEX 12.6
- PC running under Windows 7, Intel Core i5 (2.6 GHz), 4Go of RAM
- Average values on 10 randomly generated samples

Preliminary results

Computational difficulty

Results for $\sigma = 0.2\mu$

Scenarios	Variables	Constraints	Cost	Std dev.	Comp. time
1	120	60	89160	_	0.05s
10	912	564	102774	2554	0.05s
100	8832	5604	110047	684	0.4s
1000	88032	56004	110136	319	7.4s
2000	176032	112004	109924	226	20.5s
5000	440032	280004	110140	227	78.4s
10000	880032	560004	_	_	_

- Resolution with CPLEX 12.6
- PC running under Windows 7, Intel Core i5 (2.6 GHz), 4Go of RAM
- Average values on 10 randomly generated samples

Preliminary results

Value of stochastic programming

Results for $\sigma = 0.1\mu$

Scenarios	Cost	Post Optim. Eval.
1	89160	129209
10	96047	102499
100	98810	99150
1000	98860	98942
2000	98970	98928
5000	98898	98922
10000	_	_

- Resolution with CPLEX 12.6
- PC running under Windows 7, Intel Core i5 (2.6 GHz), 4Go of RAM
- Average values on 10 randomly generated samples
- Post optimization analysis carried out on 10000 out-of-sample scenarios

Preliminary results

Value of stochastic programming

Results for $\sigma = 0.2\mu$

Scenarios	Cost	Post Optim. Eval.
1	89160	173043
10	102774	117586
100	110047	110649
1000	110136	110514
2000	109924	110107
5000	110140	110085
10000	_	_

- Resolution with CPLEX 12.6
- PC running under Windows 7, Intel Core i5 (2.6 GHz), 4Go of RAM
- Average values on 10 randomly generated samples
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Plan

Conclusion

Remanufacturing planning under uncertainty

- Aggregate production planning
- Multi-product multi-period problem
- Uncertainty on the demand, returns quantity and quality

Conclusion

Remanufacturing planning under uncertainty

- Aggregate production planning
- Multi-product multi-period problem
- Uncertainty on the demand, returns quantity and quality

Two-stage stochastic programming approach

- Uncertainty represented by a set of discrete scenarios
- First-stage decisions: initial production and supply planning
- Second-stage decisions: planning adjustments applicable in practice
- Formulation of a large-size linear program
- Preliminary computational results on small instances

Perspectives

Short-term perspectives

- Solve instances with more products and more periods
- Improve sample generation
- Develop an efficient solution approach

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Short-term perspectives

- Solve instances with more products and more periods
- Improve sample generation
- Develop an efficient solution approach

Mid-term perspectives

- Improve the production planning problem representation:
  - more activities: sorting/grading, part refurbishing
  - hybrid manufacturing/remanufacturing system
  - non-linear production costs
- Improve the uncertainty representation
  $\rightarrow$ multi-stage decision process

Thank you for your attention !