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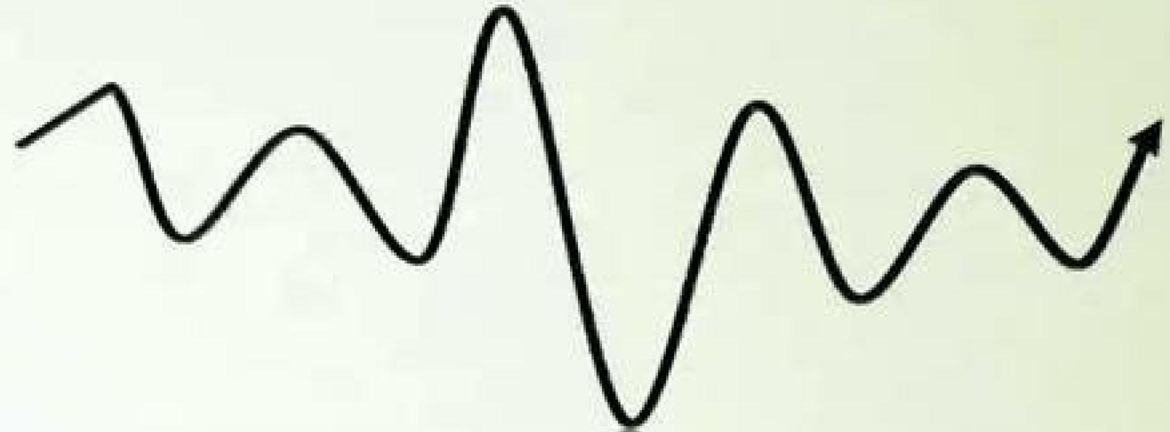

The dynamics of closed-loop supply chains

Borja Ponte (University of Oviedo, Spain)

Online seminar organised by the ReTraCE, ProCEedS and JUST2CE *projects*
25 May 2022

This presentation revolves around the article "*Quality grading of returns and the dynamics of remanufacturing*" (*International Journal of Production Economics*, 2021), written together with Dr Salvatore Cannella (U. of Catania), Dr Roberto Dom Naim and Prof Aris A. Syntetos (Cardiff U.).

Index of this presentation

The dynamics of closed-loop supply chains

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25 May 2022

1
Personal background

1. Gijón, Asturias (x-2016)

Industrial Engineering (Industrial Management)

PhD in Operations Management:

"Bullwhip Effect reduction through AI techniques"

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2. Cardiff, Wales, UK (2017-2018)

Resilient Remanufacturing Networks:
Forecasting, Informatics, and Holons

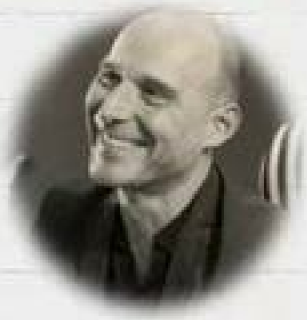
Thanos E. Goltsos

Borja Ponte

Shixuan Wang

Ying Liu

Mohamed M. Naim



Aris A. Syntetos

2. Cardiff, Wales, UK (2017-2018)

RESILIENT REMANUFACTURING NETWORKS (ReRuN): FORECASTING, INFORMATICS, AND HOLONS

Policy advisors

wrap

Conseil Européen de Remanufacture

EPSRC
Engineering and Physical Sciences Research Council

Industry partners

PANALPINA on 6 continents

brother at your side

QIOPTIQ Photonics for Innovation An Excelitas Technologies Company

BT

MCT ReMan Ltd

3. Milton Keynes, England, UK (2018-2019)

Lecturer in Operations Management at **The Open University Business School**

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4. Gijón, Asturias (2020-X)

Lecturer in Business Administration at the **Polytechnic School of Engineering** of the **University of Oviedo**

Universidad de Oviedo

2

Context:
The pillars of our research

2. Context: The pillars of our research

<u>Supply chains can be dynamically designed</u>
to improve product availability, reduce operational costs, and create a stable working environment for all actors involved

2. Context: The pillars of our research

MANAGING THE FLOW OF MATERIALS IN A SUPPLY CHAIN…

It is mainly about…

Optimising the satisfaction of customers

while…

Minimising the total supply chain inventory

→ The perspective of **inventories**

and

Maximising the stability of the supply chain operations

→ The perspective of **orders**

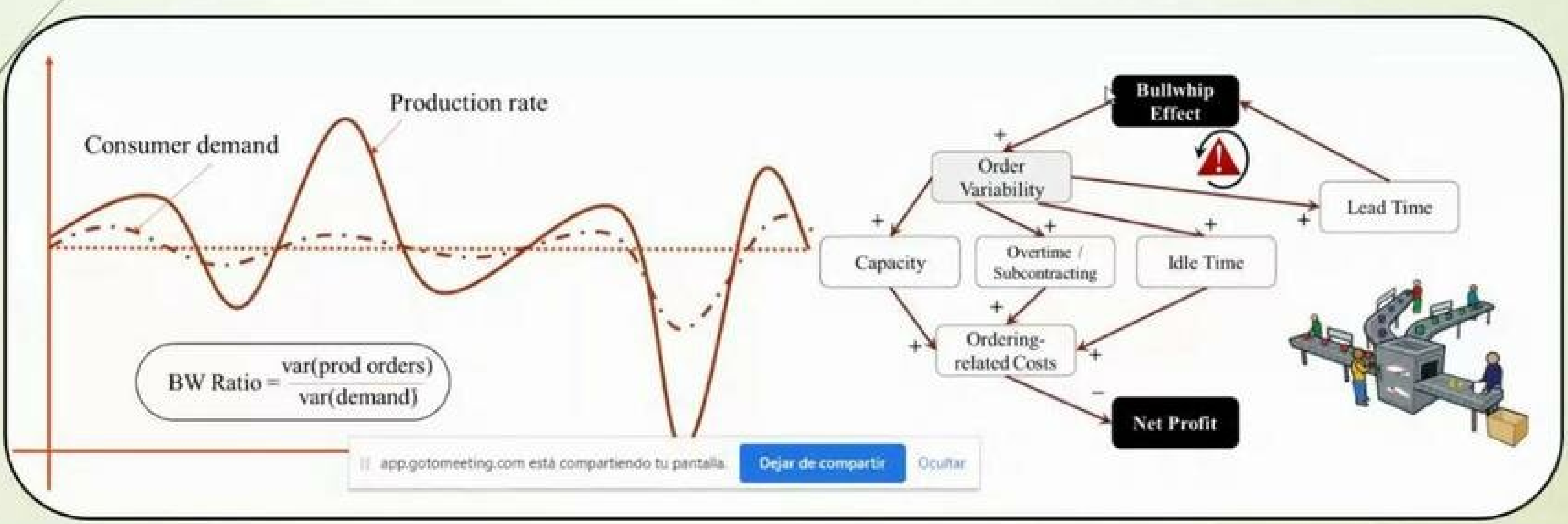
…e often analyzed independently but they are essentially two sides of the same coin!

2. Context: The pillars of our research

What do we mean by '***supply chain dynamics***'?

- This discipline explores the ***interaction between the different elements*** (nodes, policies, methods, and structures) ***of a supply chain*** by considering ***the evolution of the main variables that define its behaviour*** (basically, inventories and orders).

(2) The perspective of orders



2. Context: The pillars of our research

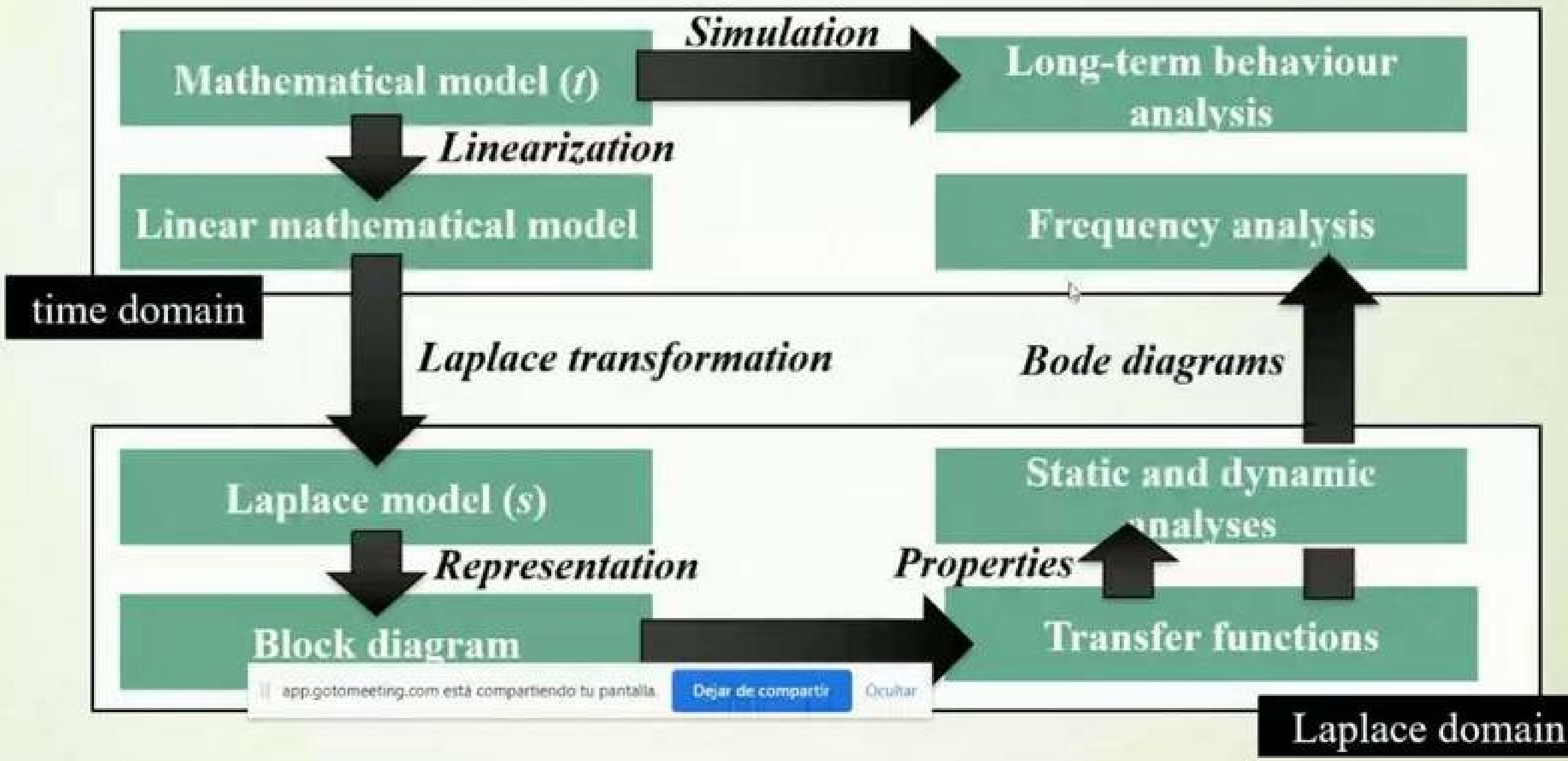
What ***techniques*** do we use?

- The dynamics of supply chains can be investigated using a ***wide variety of techniques***, including:
  - **Simulation** (e.g. discrete-event, agent-based, etc.) and **experimental techniques**
  - **Stochastic calculus**
  - **Control theory**

2. Context: The pillars of our research

What ***techniques*** do we use?

- Our ***methodological approach*** based on **control theory**…



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3

Motivations and goals of this work

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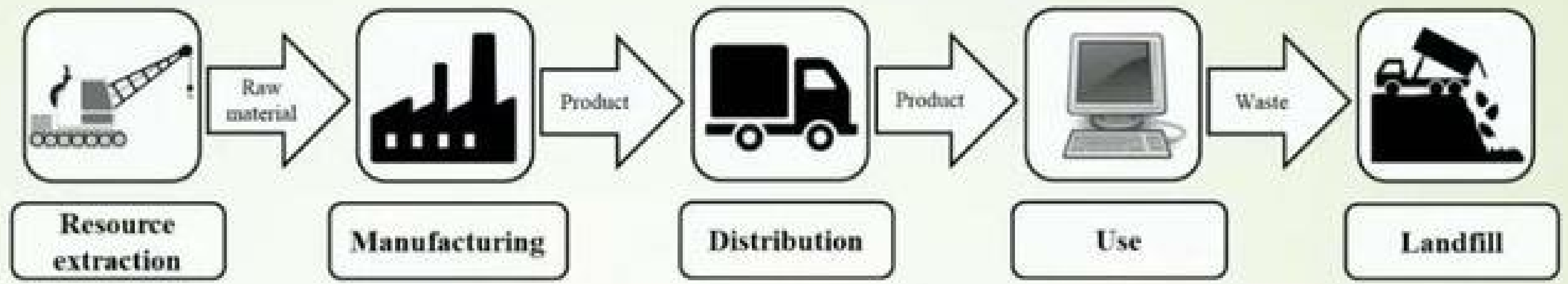
3. Motivations and goals of this work

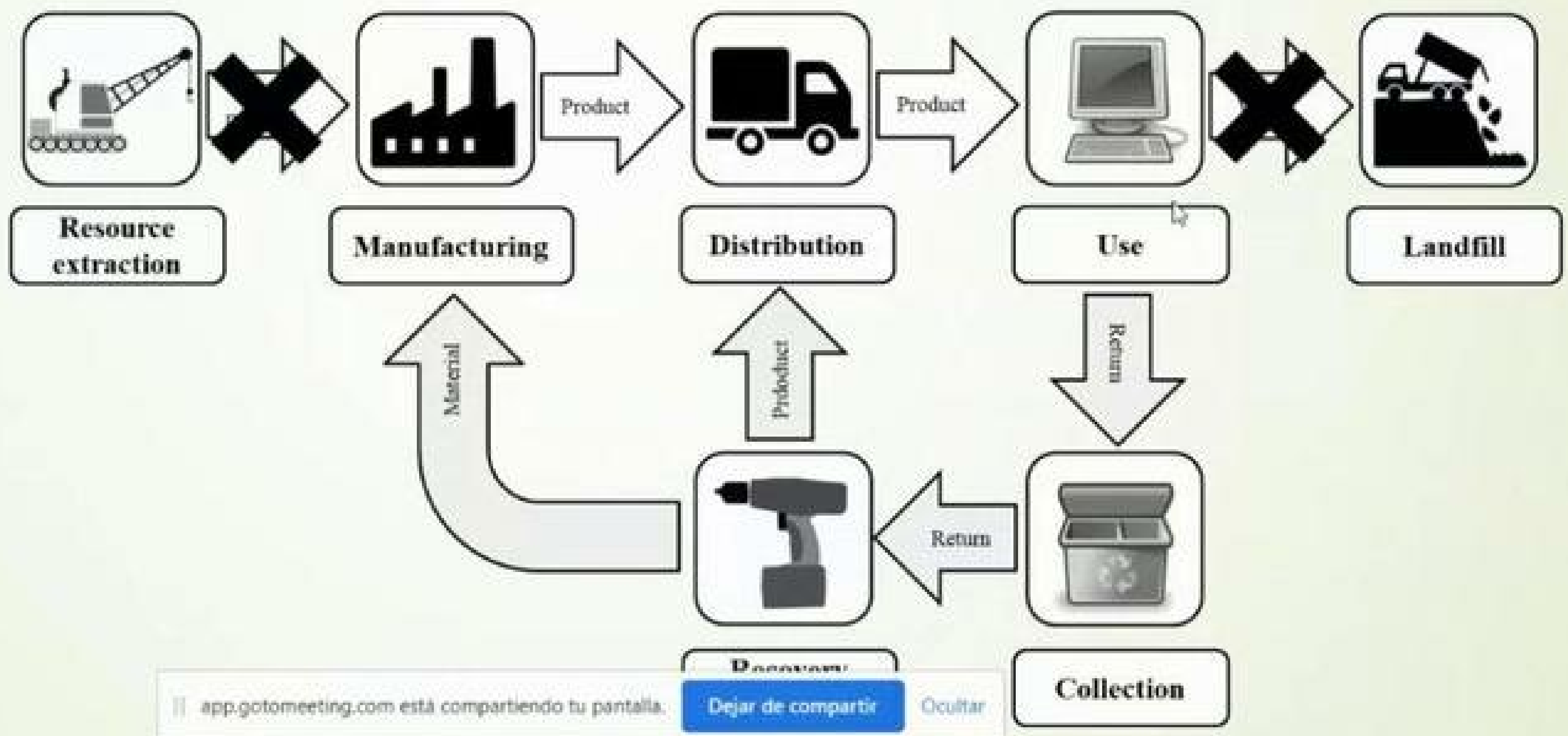
- The **world economy** is currently evolving from a linear to a **circular model,** which entails:
  - *Environmental* opportunities, and
  - *Economic* opportunities.

- Consequently, the **supply chain paradigm** is shifting into a **closed-loop archetype**, which includes *collection* and *recovery* processes, such as **remanufacturing**.

Traditional open-loop supply chain model



Emerging closed-loop supply chain model



3. Motivations and goals of this work

- A crucial characteristic that differentiates closed-loop supply chain contexts from traditional open-loop supply chain contexts is the **uncertainty in the quantity and the <u>quality</u> of returned products.**

- Despite that, most studies assume a **single quality grade** for all returns. This premise, aimed at reducing modeling and analysis efforts, may result in "**elegant solutions addressing non-existent problems**" (Guide & van Wassenhove, 2009).

3. Motivations and goals of this work

... To what extent does quality matter?

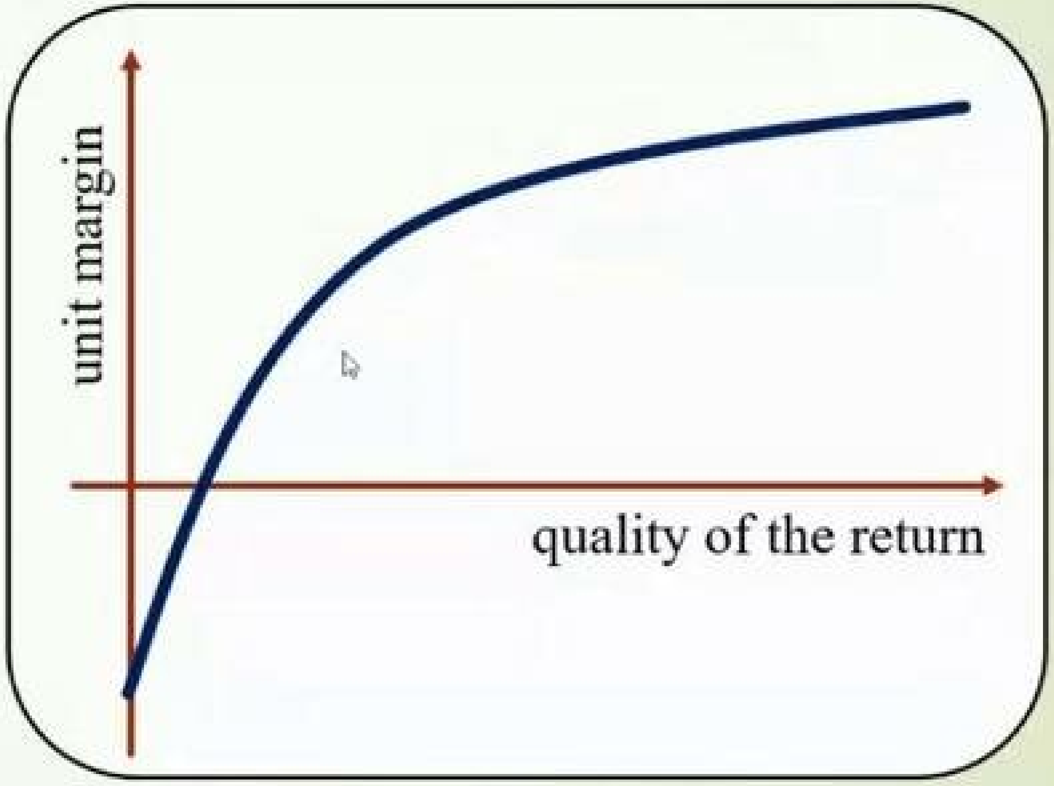
- *"Based on our conversations with the managers of remanufacturing facilities, the uncertainty in the quality of the returns presents a much larger problem than the uncertainty in the quantity of returns." (Denizel et al., 2010)*

- *The authors reported that, at IBM's remanufacturing facilities, quality variation may result in a 300% difference in the required recovery time*

3. Motivations and goals of this work

… To what extent does quality matter?

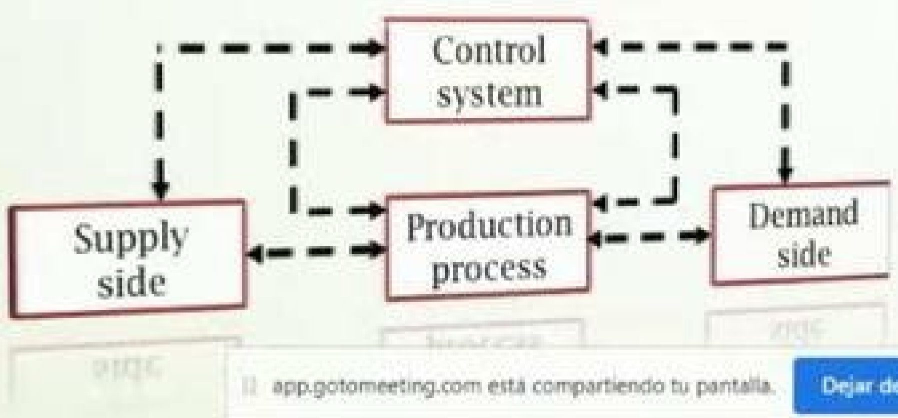
- *"We cost the program as a single average cost per product family knowing that we will lose money on some cores (bad quality) but make money on other cores (good quality)" (Briggs, 2017)*
- *Zikopoulos (2017) concluded that ignoring quality uncertainty in the modelling of closed-loop supply chains results in extensive additional costs, even for relatively low values of quality varic*



3. Motivations and goals of this work

How can managers deal with quality uncertainties?

Quality grading (i.e. categorising the returns according to their condition as soon as they arrive to the remanufacturing facitlity) is a common industrial practice aimed at **preventing that the *supply uncertainty (of returns)* translates into *process uncertainty***.



3. Motivations and goals of this work

The **effects of the variable quality of cores** and/or **value of quality grading** have been explored from different perspectives:

- Aras et al. (2004) investigated the conditions under which categorising returns according to their quality results in cost savings.
- *Zikopoulos & Tagaras (2008)* determined conditions under which it is optimal to set up a sorting procedure with limited accuracy (to identify non-remanufacturable items) to avoid incurring costs of disassembling bad units.
- *Ferguson et al. (2009)* estimated the cost-effectiveness of quality-based categorisation of returns by considering the cost of remanufacturing, the holding cost, and the unit salvage value of cores.
- *Su & Xu (2014)* investigated the buffer allocation problem for hybrid manufacturing/remanufacturing systems with quality grading.
- *Yanıkoğlu & Denizel (2021)* studied the same problem as *Ferguson et al. (2009)* when the quality of the cores cannot be perfectly known at inspection (quality level uncertainty).
- …

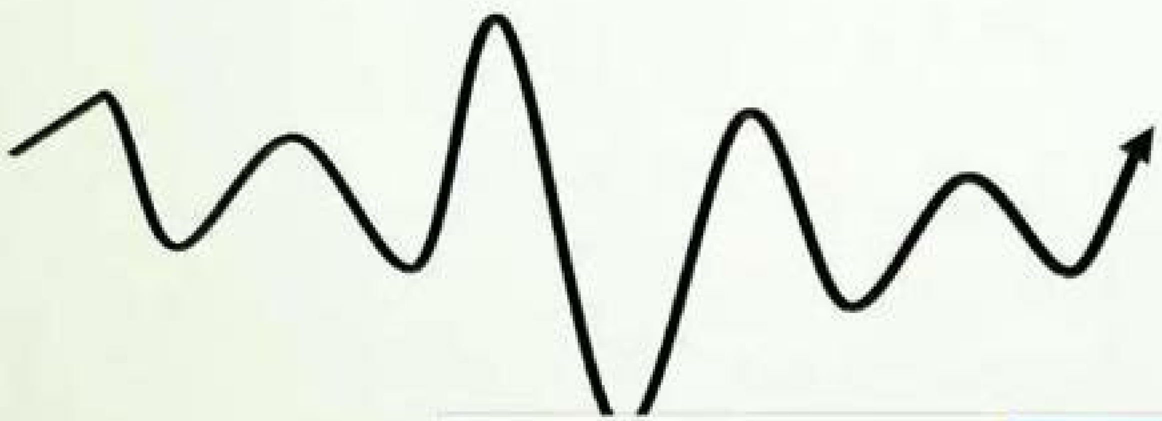
3. Motivations and goals of this work

However, **the value of quality grading** has not been investigated **from the perspective of supply chain dynamics**:

Research question: **How does quality grading impact on the dynamic behaviour of closed-loop supply chains?**

(1) The perspective of *order variability*

(2) The perspective of *inventory variability*



The understanding of the dynamic consequences of quality grading in closed-loop supply chains would allow for a better design of these systems

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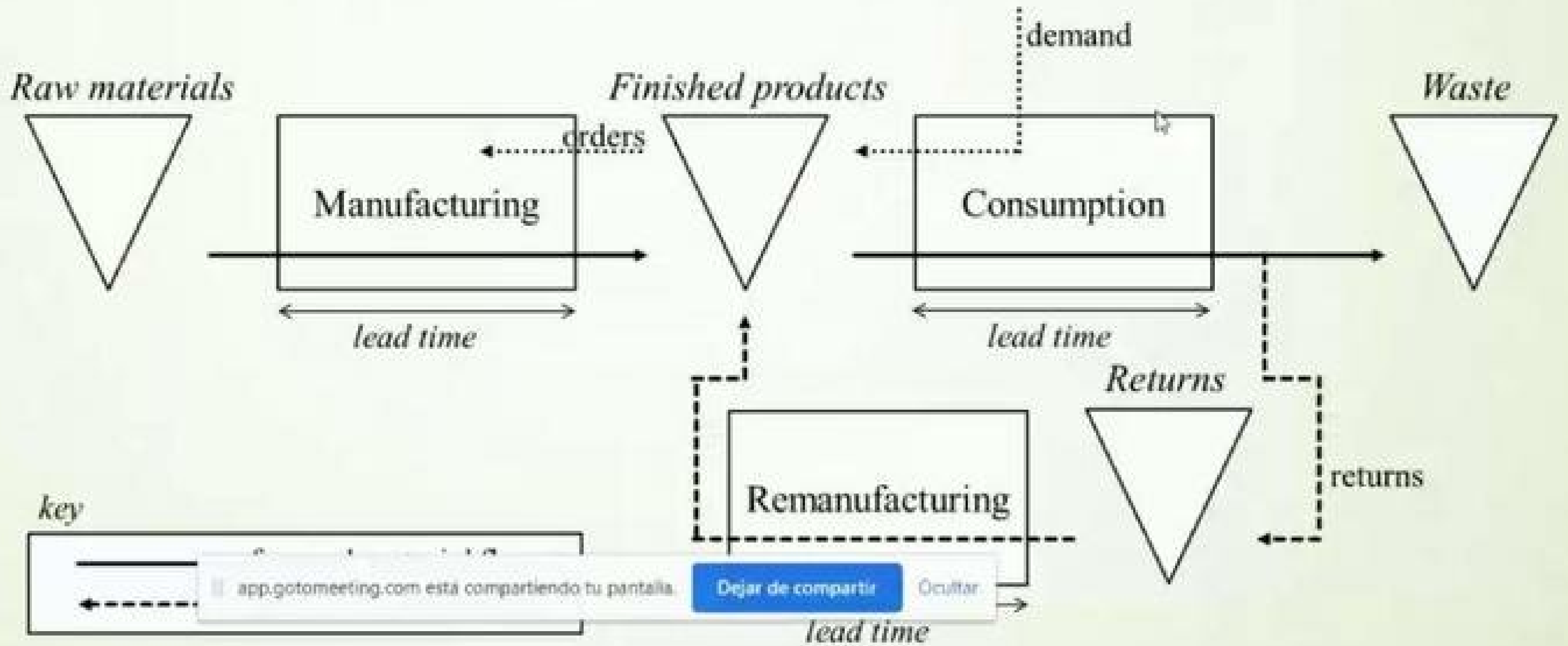
4

Closed-loop supply chain model

4. Closed-loop Supply chain model

We explore a closed-loop supply chain that is based on a **hybrid manufacturing-remanufacturing system** (HMRS), in line with previous works in this field (from Tang & Naim, 2004 to Hosoda et al., 2021).

- *Practical applications: circular economy contexts, where the assumption of perfect substitution (between new and remanufactured products) holds, e.g. spare parts industry.*



4. Closed-loop Supply chain model

Relevant assumptions **on the <u>forward flow</u> of materials:**

- *<u>Proportional order-up-to policy</u> in the serviceable inventory for regulating the forward flow of materials* – a reasonable option for finding an appropriate trade-off between order and inventory variabilities.

Tang and Naim's (2005) adaptation of the POUT policy to HMRSs (*type-3*)

$$o_t = (\hat{d}_t - rr_t) + (1/Ti) \cdot (SS - ns_t) + (1/Tw) \ldots$$

- o_t: order in period *t*
- $\hat{d}_t$: demand forecast in period *t*
- ns_t: remanufactured returns in period *t*
- SS : safety stock
- ns_t : net stock in period *t*
- Ti : on-hand inventory controller
- Tw : on-order-inventory controller
- ite of the pipeline lead time
- w_t : work-in-progress in period *t*

4. Closed-loop Supply chain model

Relevant assumptions **on the forward flow of materials:**

- *Proportional order-up-to policy in the serviceable inventory for regulating the forward flow of materials* – a reasonable option for finding an appropriate trade-off between order and inventory variabilities.
- *Exponential smoothing forecasting of the demand* – a popular method in practice.

Tang and Naim's (2005) adaptation of the POUT policy to HMRSs (*type-3*)

$$o_t = (\hat{d}_t - rr_t) + (1/Ti) \cdot (SS - ns_t) + (1/Tw) \cdot$$

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4. Closed-loop Supply chain model

Relevant assumptions **on the <u>reverse flow</u> of materials:**

4. Closed-loop Supply chain model

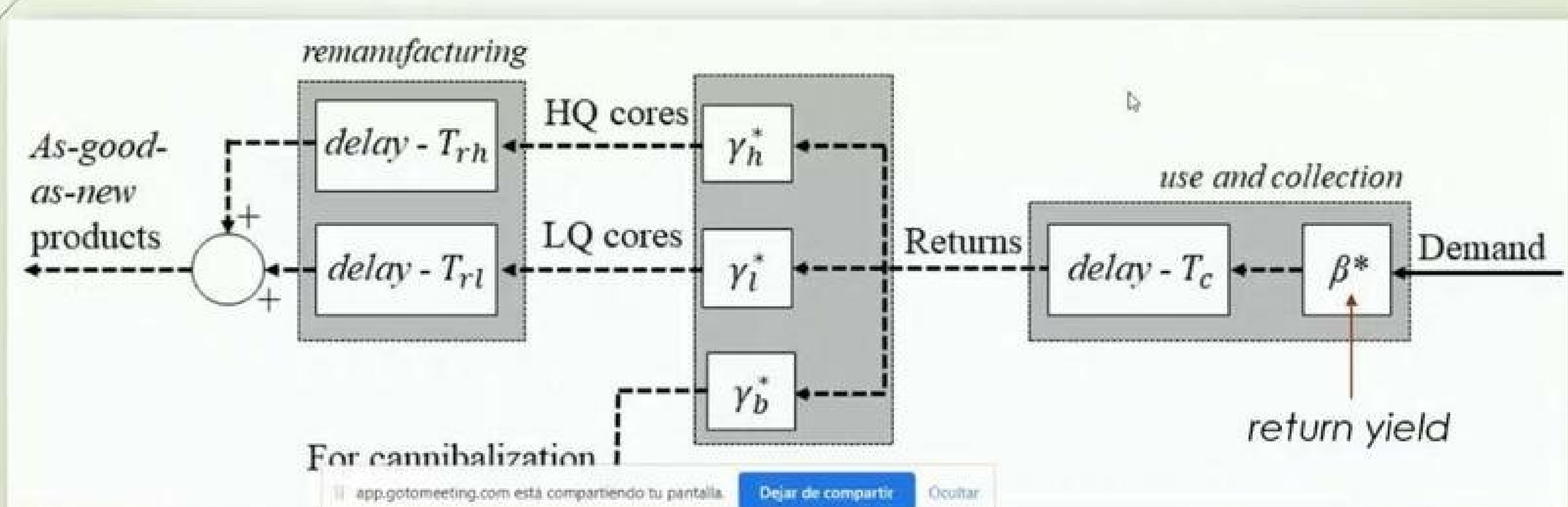
Relevant assumptions **on the <u>reverse flow</u> of materials:**

- *<u>Push policy</u> in the recoverable inventory for regulating the reverse flow of materials* – a decision that 'fits well with the ethics of sustainability' (Hosoda & Disney, 2018) as it prioritizes remanufactured over new items.

4. Closed-loop Supply chain model

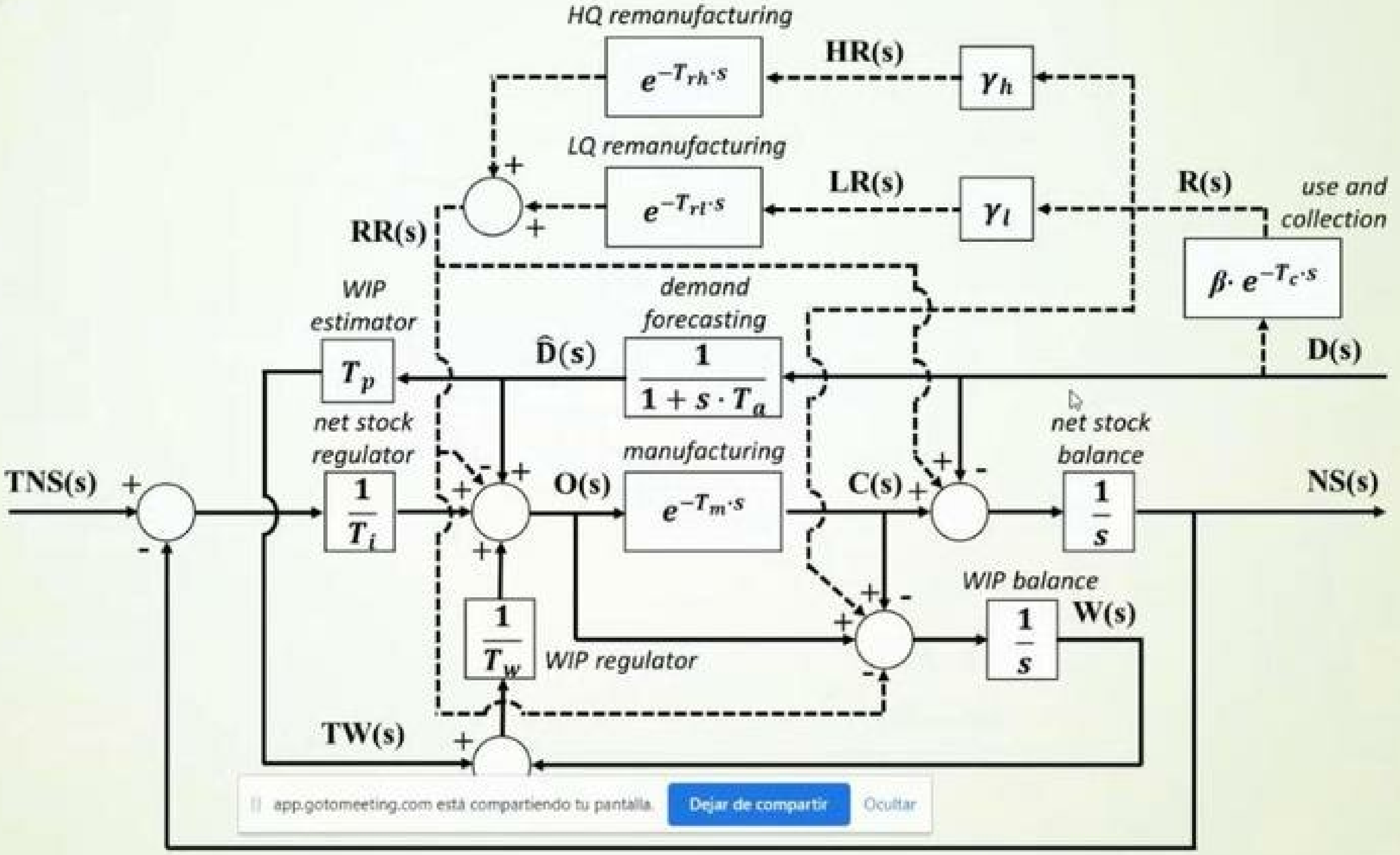
Relevant assumptions **on the reverse flow of materials:**

- *Push policy in the recoverable inventory for regulating the reverse flow of materials* – a decision that 'fits well with the ethics of sustainability' (Hosoda & Disney, 2018) as it prioritizes remanufactured over new items.
- *Three categories of returns:*



4. Closed-loop Supply chain model

Block diagram representation of the system:



4. Closed-loop Supply chain model

Transfer functions:

$$\frac{O(s)}{D(s)} = \frac{(T_m s+1)\left(T_i T_w s + T_a T_w s + T_i T_p s + T_w\right)}{(T_a s+1)(T_i T_m T_w s^2 + T_i T_w s + T_i T_m s + T_w)} - \beta \frac{(T_m s+1)(a_{OD} s^2 + b_{OD} s + c_{OD})}{(T_c s+1)(T_{rh} s+1)(T_{rl} s+1)(T_i T_m T_w s^2 + T_i T_w s + T_i T_m s + T_w)}$$

where $a_{OD} = \gamma_h T_i T_{rl}(T_w + T_{rh}) + \gamma_l T_i T_{rh}(T_w + T_{rl})$, $b_{OD} = \gamma_h(T_w T_{rl} + T_w T_i + T_i T_{rh}) + \gamma_l(T_w T_{rh} + T_w T_i + T_i T_{rl})$, and $c_{OD} = (\gamma_h + \gamma_l)T_w$.

4. Closed-loop Supply chain model

Transfer functions:

$$\frac{O(s)}{D(s)} = \frac{(T_m s + 1)\left(T_i T_w s + T_a T_w s + T_i T_p s + T_w\right)}{(T_a s + 1)(T_i T_m T_w s^2 + T_i T_w s + T_i T_m s + T_w)} - \beta \frac{(T_m s + 1)(a_{OD} s^2 + b_{OD} s + c_{OD})}{(T_c s + 1)(T_{rh} s + 1)(T_{rl} s + 1)(T_i T_m T_w s^2 + T_i T_w s + T_i T_m s + T_w)}$$

where $a_{OD} = \gamma_h T_i T_{rl}(T_w + T_{rh}) + \gamma_l T_i T_{rh}(T_w + T_{rl})$, $b_{OD} = \gamma_h(T_w T_{rl} + T_w T_i + T_i T_{rh}) + \gamma_l(T_w T_{rh} + T_w T_i + T_i T_{rl})$, and $c_{OD} = (\gamma_h + \gamma_l) T_w$.

$$\frac{NS(s)}{D(s)} = -\frac{T_i\left(T_a T_m T_w s^2 + T_m T_w s + T_a T_w s + T_a T_m s - T_p + T_m\right)}{(T_a s + 1)(T_i T_m T_w s^2 + T_i T_w s + T_i T_m s + T_w)} + \beta \frac{T_i(a_{NSD} s^2 + b_{NSD} s + c_{NSD})}{(T_c s + 1)(T_{rh} s + 1)(T_{rl} s + 1)(T_i T_m T_w s^2 + T_i T_w s + T_i T_m s + T_w)}$$

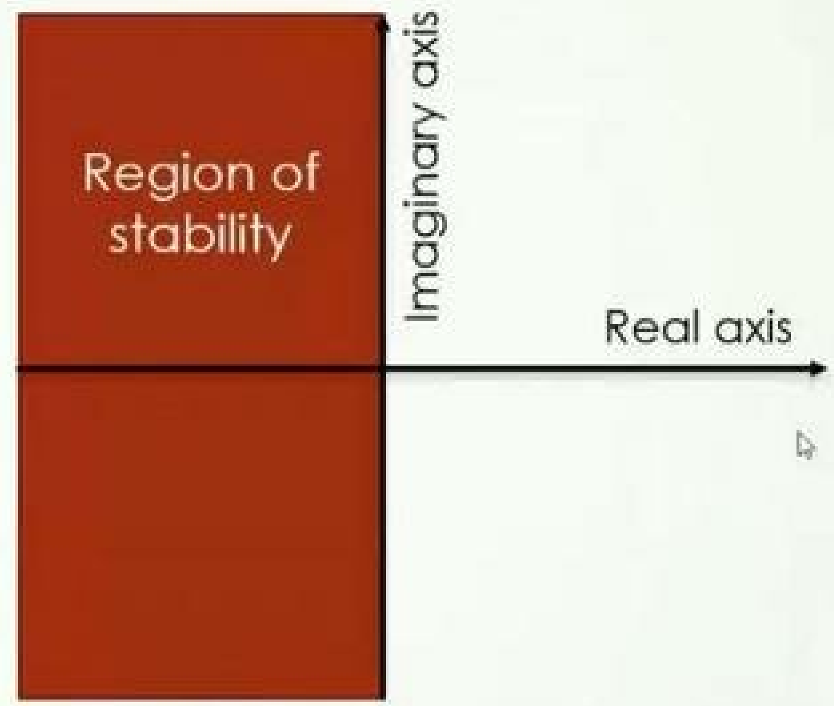
where $a_{NSD} = (\gamma_h T_{rl} + \gamma_l T_{rh}) T_w T_m$, $b_{NSD} = \gamma_h(-T_{rh} T_{rl} + T_w T_m + T_m T_{rl}) + \gamma_l(-T_{rh} T_{rl} + T_w T_m + T_m T_{rh})$, and $c_{NSD} = (\gamma_h + \gamma_l) T_m - (\gamma_h T_{rh} + \gamma_l T_{rl})$.

5

Stability and steady-state analysis

5. Stability and steady-state analysis

It is known that the **stability of the system** depends on the **position of its poles** in the complex plane.



Conclusion of the stability analysis:

"The system is stable for all the possible logical combinations of its parameters"

5. Stability and steady-state analysis

Analytically, we have obtained the **optimal *Tp (estimate of the pipeline lead time)*** from the perspective of the **trade-off between inventory holding costs and service level**:

$$o_t = (\hat{d}_t - rr_t) + (1/Ti) \cdot (SS - ns_t) + (1/Tw) \cdot (Tp \cdot \hat{d}_t - w_t)$$

$$T_p = (1-\beta)T_m + \beta(\gamma_h\, T_{rh} + \gamma_l\, T_{rl})$$

average return yield

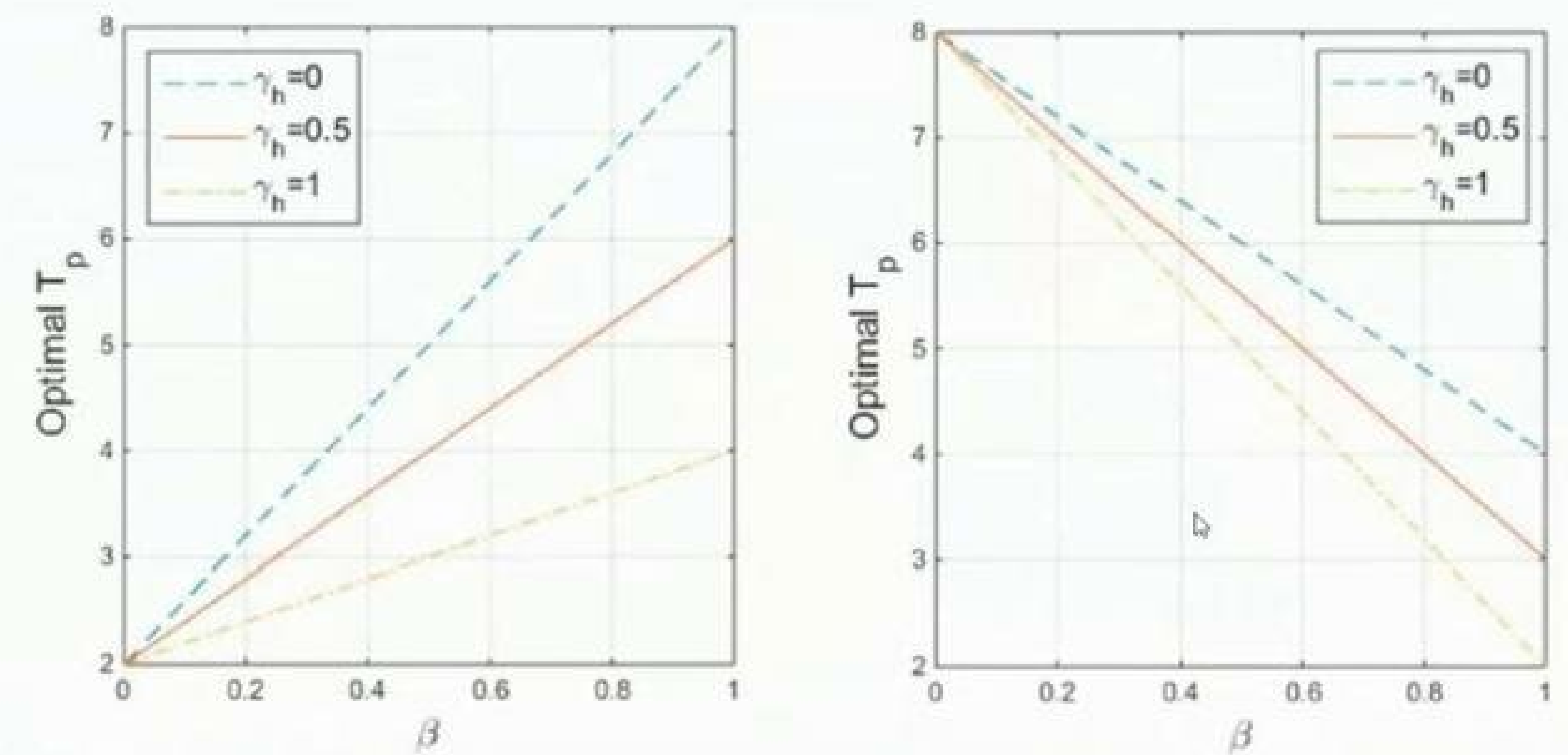
manufacturing lead time

average HQ / LQ yield

remanufacturing lead time of HQ / LQ returns

This setting avoids any long-term drift in the serviceable inventory; hence ensuring that the average position of this inventory is the safety stock.

5. Static analysis

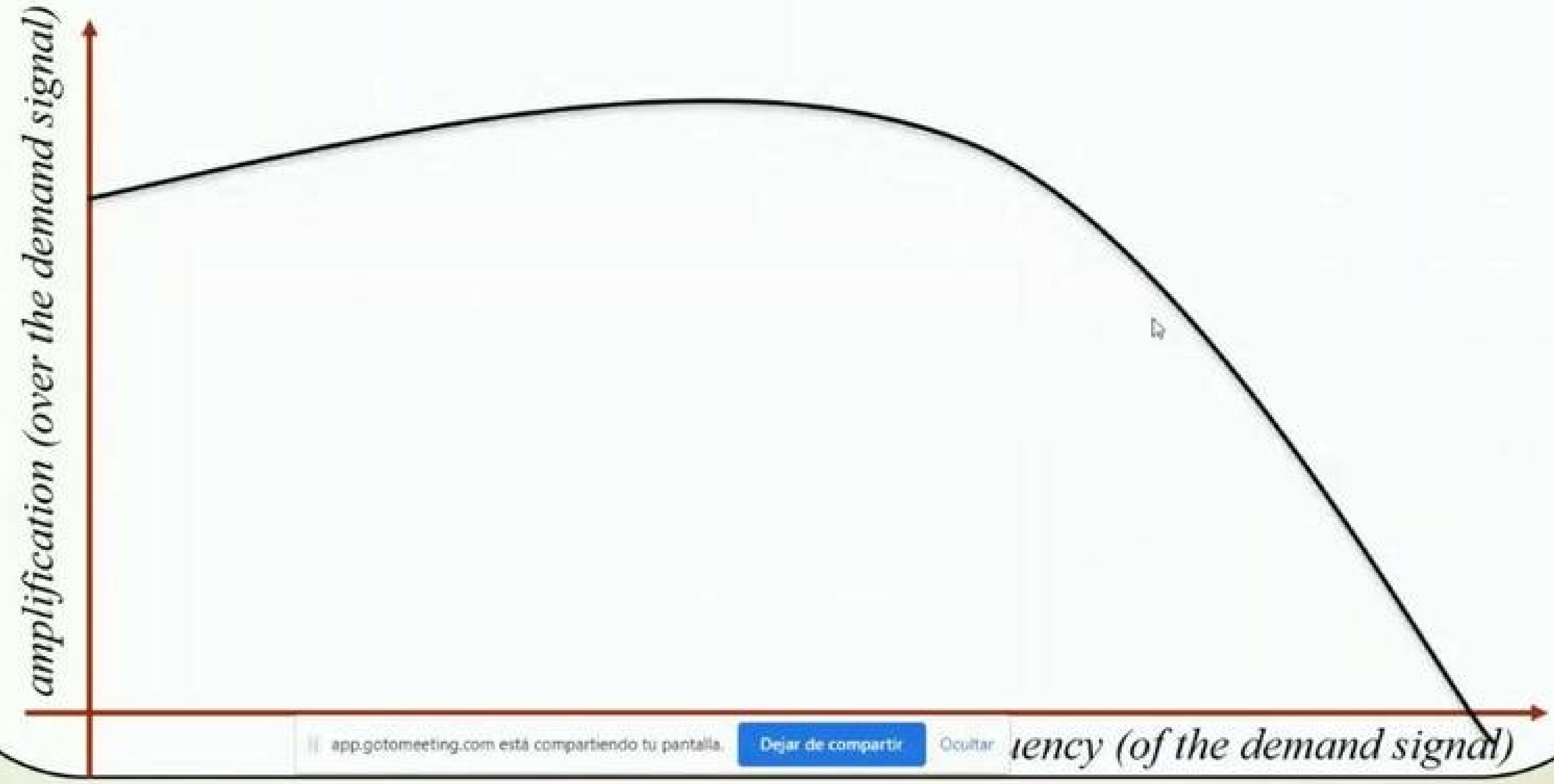


(a) $T_m = 2, T_{rh} = 4, T_{rl} = 8$ (b) $T_m = 8, T_{rh} = 2, T_{rl} = 4$

6
Dynamic analysis

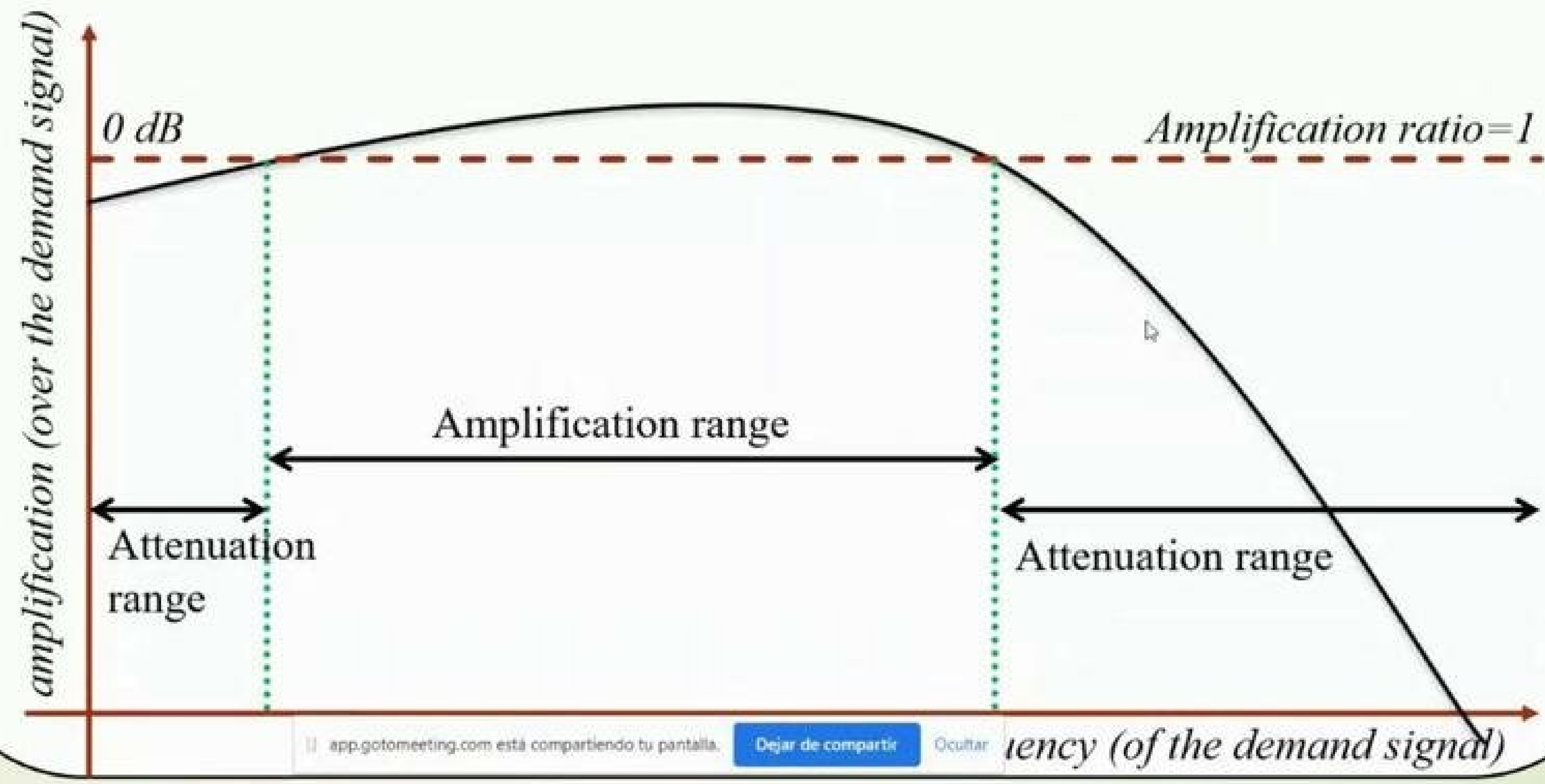
6. Dynamic analysis

A brief introduction to Bode plots and their interest in the OM/R field:



6. Dynamic analysis

A brief introduction to Bode plots and their interest in the OM/R field:



6. Dynamic analysis

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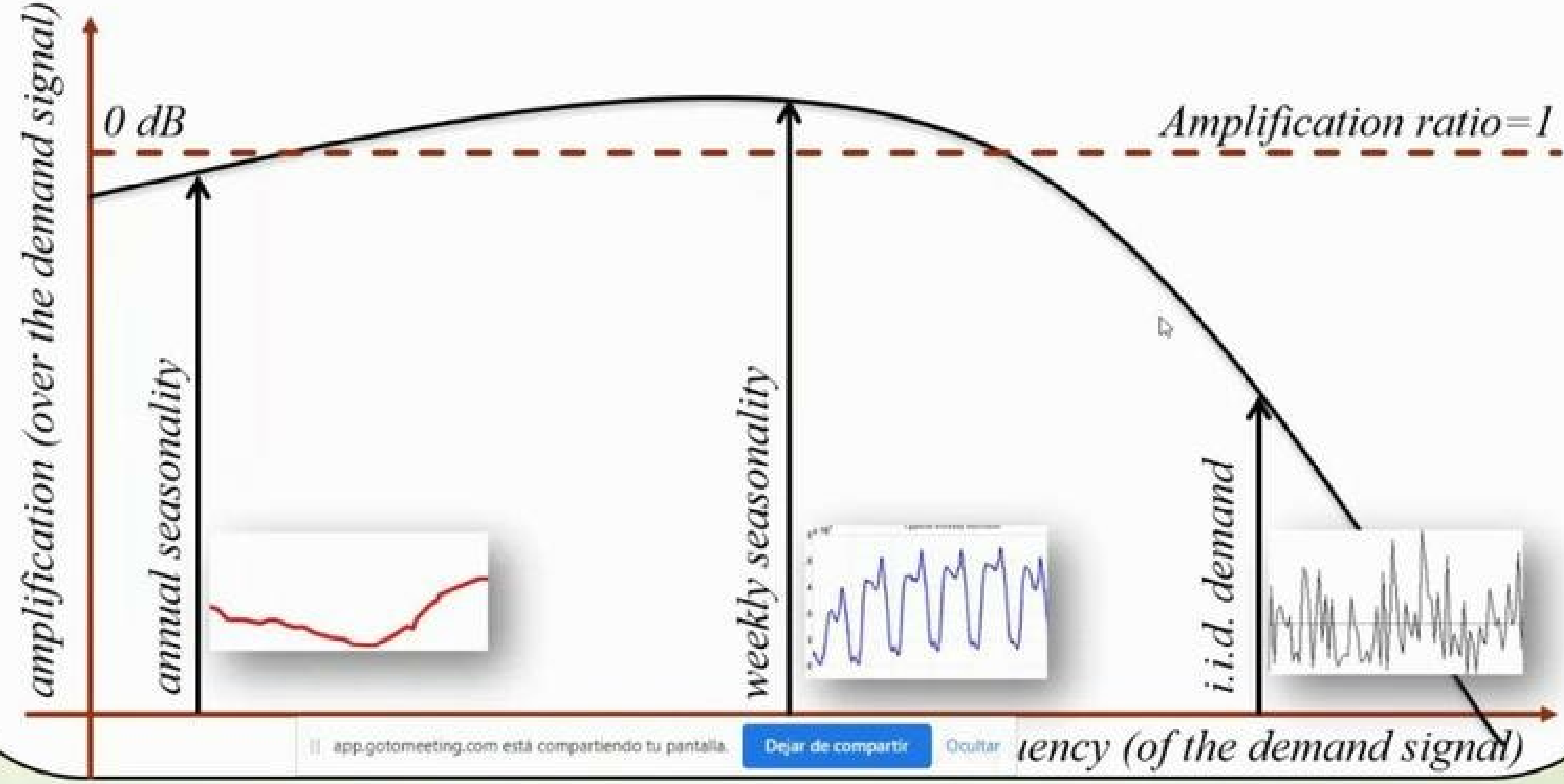


6. Dynamic analysis

A wider varity of scenarios is analysed in Ponte et al. (2021)

Experimental design:

- For the noise factors, we assume:
  - **Manufacturing lead time:** T_m = 8 *days*
  - **Remanufacturing lead time:** T_{rh} = 1 *day*; T_{rl} =7 *days*
  - **Consumption lead time:** T_c = 32 *days*
  - **Average return rate:** β = 80%

- For the control factors, we assume:
  - **Exponencial smoothing factor:** T_a = 16 *days*
  - **On-hand inventory controller:** T_i = 8 *days*
  - **On-order inventory controller:** T_w = 8 *days*
  - **Estimated** [illegible]

"*A good control setting*" for CLSCs (Tang & Naim, 2004)

6. Dynamic analysis

(1) The perspective of *order variability*　　(2) The perspective of *inventory variability*

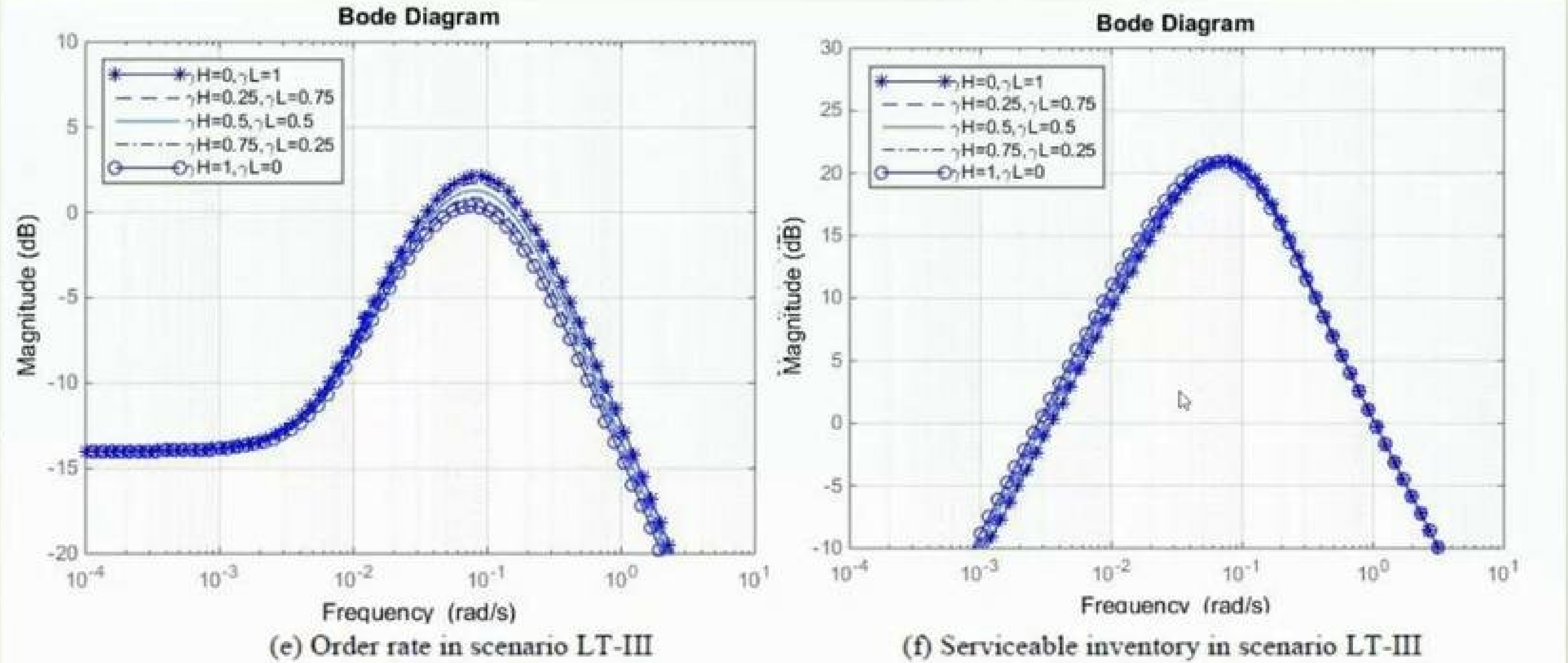
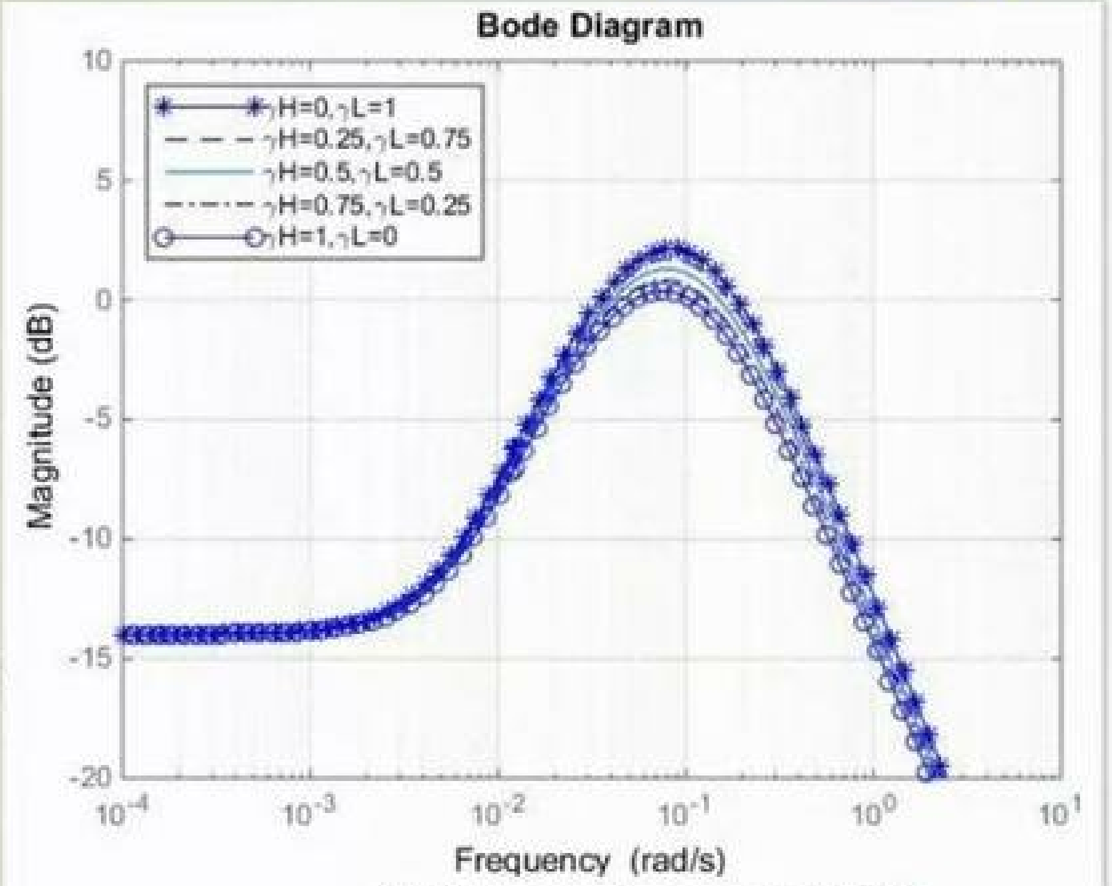


Figure 6. Bode diagram of the order rate and the serviceable inventory for different returns qualities.

6. Dynamic analysis

(1) The perspective of order variability



(e) Order rate in scenario LT-III

Quality grading always smooths the production rate of CLSCs.

- As can be expected, the improvement is more pronounced as the percentage of HQ returns grows.

- The value of quality grading is higher for mid-frequency demands, where the original system behaves poorly.

<u>Note:</u>
0 dB → Ampl: 0
0.5 dB → Ampl: 6%
1 dB → Ampl: 12%
1.5 dB → Ampl: 19%
2 dB → Ampl: 26%
...
5 dB → Ampl: 78%

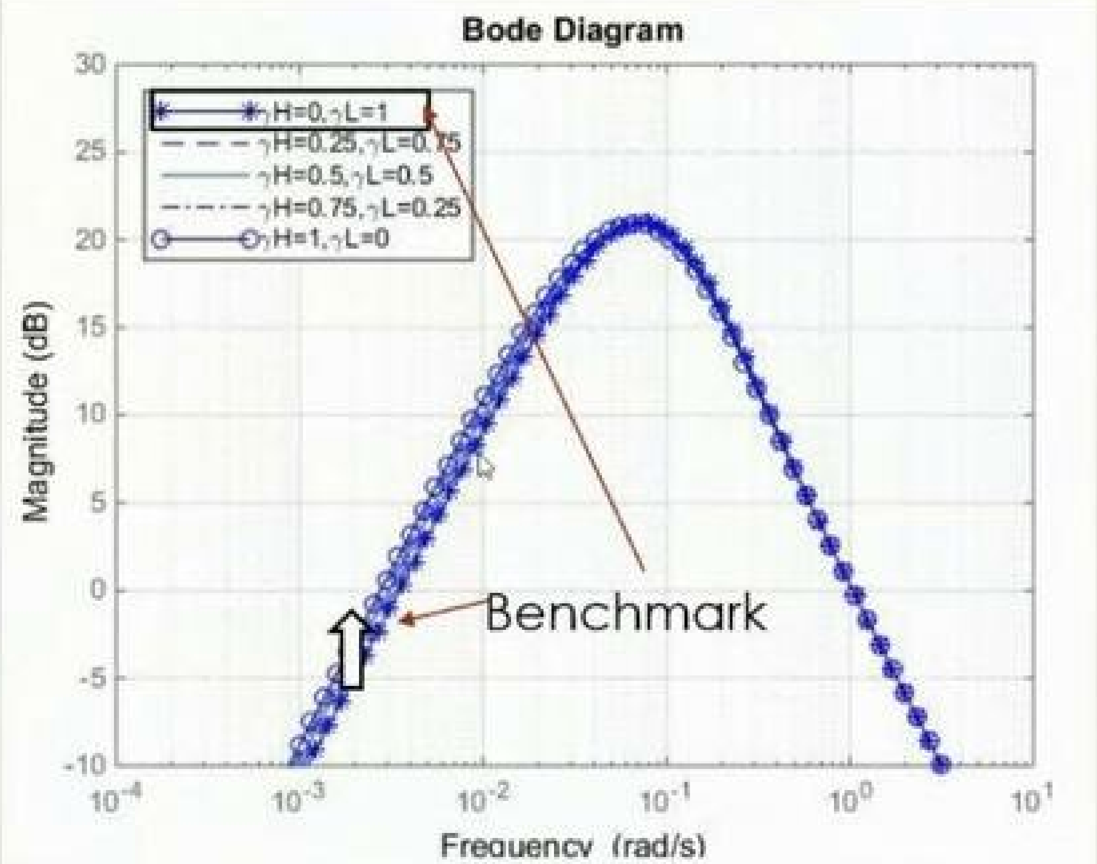
6. Dynamic analysis

Quality grading mainly impacts on the inventory dynamics for low-frequency demands.

- Interestingly, in these cases improving the quality of the returns provokes a decrease in the inventory performance of the system.

- This may be termed a 'quality paradox', and can be interpreted as a consequence of the widely documented 'lead-time paradox' in hybrid systems (e.g. van der Laan et al., 1999).

(2) The perspective of *inventory variability*



(f) Serviceable inventory in scenario LT-III

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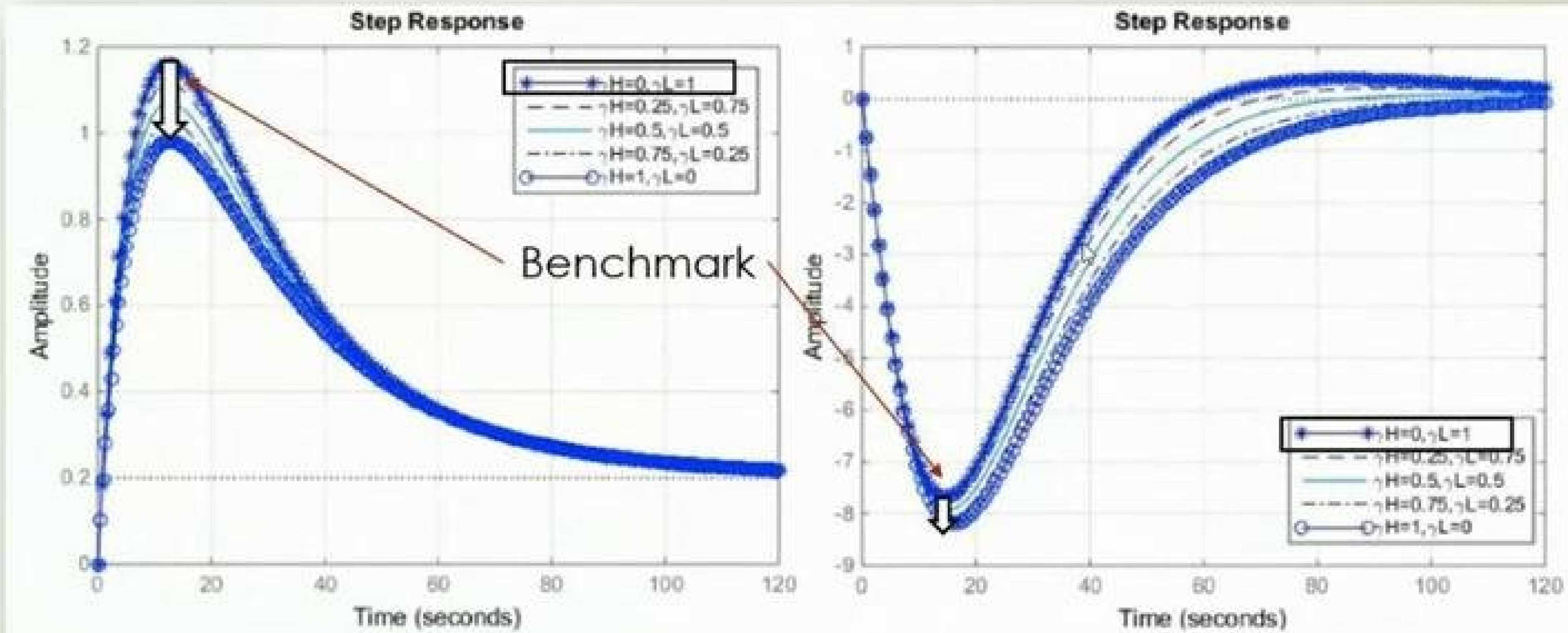
6. Dynamic analysis

The main ideas can also be observed by analysing the unit-step response…



(f) Serviceable inventory in *scenario LT-III*

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7

Findings, implications and next steps

Three main findings…

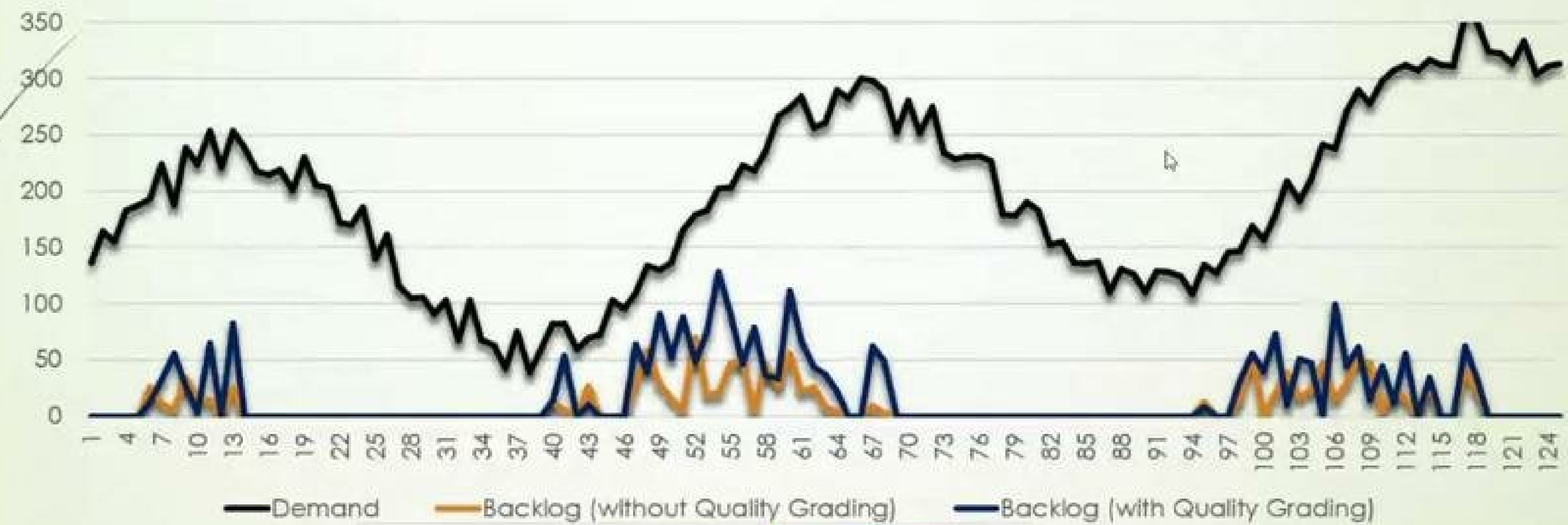
7. Findings, implications, and next steps

1. In addition to other benefits that have already been discussed in the literature, ***implementing a quality grading policy smooths the operations of closed-loop supply chains****, especially for mid- and high-frequency demands.*

Three main findings…

7. Findings, implications, and next steps

2. However, implementing a quality grading policy ***may decrease the inventory performance of the system*** *(i.e. reduce customer satisfaction and/or increase inventory costs). Nonetheless, the reduction is only significant for low-frequency demands, as a direct consequence of the remanufacturing lead time paradox.*



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Three main findings…

7. Findings, implications, and next steps

3. ***Over- and under-estimating the pipeline lead time significantly decreases the performance of the closed-loop supply chain.***

$$T_p = (1 - \beta)T_m + \beta(\gamma_h\, T_{rh} + \gamma_l\, T_{rl})$$

- Consequences of over-estimating the pipeline lead time:
  - *Significant increase in the order variability.*

- Consequences of under-estimating the pipeline lead time:
  - *Significant increase in the inventory variability.*

This emphasizes the role of information transparency and accurate estimation of the various supply chain parameters.

Key implications

7. Findings, implications, and next steps

1

Categorizing the incoming returns into several quality grades enables the development of more efficient circular economy systems. Specifically, the design of a parallel remanufacturing structure, with lines for cores in similar conditions, proves to be a useful instrument for reducing Bullwhip in closed-loop supply chains.

Key implications

7. Findings, implications, and next steps

1. **Categorizing the incoming returns into several quality grades enables the development of more efficient circular economy systems.** Specifically, the design of a parallel remanufacturing structure, with lines for cores in similar conditions, proves to be a useful instrument for reducing Bullwhip in closed-loop supply chains.

2. **Quality-grading implementation requires a firm understanding of the nature of customer demand**, as the seasonanility of customer demand significantly affects the impact of quality grading on the dynamics of closed-loop supply chains. Relevantly, for closed-loop supply chains operating in anomalous market environments, quality-grading policies may accentuate the stock-out risk.

3. Closed-loop supply chains with a quality-grading policy and parallel remanufacturing have the potential to outperform HMRSs with no grading. **To realize this potential, managers need to be fully aware of the value of information visibili[illegible]ata in these supply chains.**

7. Findings, implications, and next steps

Future research questions:

- *What if…*

7. Findings, implications, and next steps

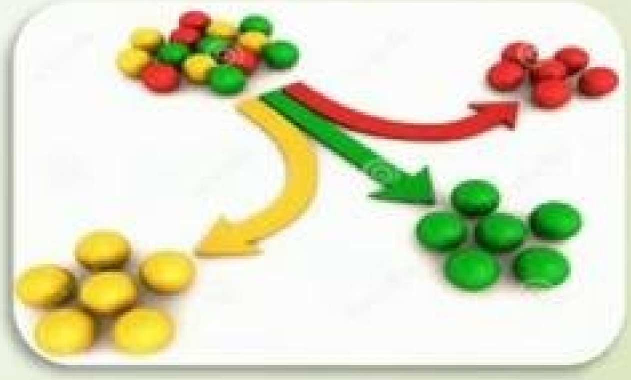
Future research questions:

- *What if…*
  - *New and remanufactured products are not perfect substitutes?*

7. Findings, implications, and next steps

Future research questions:

- *What if…*
  - *New and remanufactured products are not perfect substitutes?*
  - *We employ different control policies for the closed-loop supply chain and/or different forecasting mechanisms?*
  - *The grading process is not 100% accurate?*



Thank you for your attention!
Any questions?

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